# FLAT SURFACE LAPPING: PROCESS MODELING IN AN INTELLIGENT ENVIRONMENT

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ABSTRACT

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The process of lapping has been long considered an art due to the tremendous amount of variability and subjectivity involved. The quality of lapping differs from operator to operator and the results are highly inconsistent. The material removal rate, surface finish, and flatness all depend on the proper control of lapping parameters such as lapping pressure, lapping speed of rotation, lap ring material, weight and size, abrasive size and type, workpiece material and hardness. To attain the desired outcomes, it is imperative to select proper values for the lapping control parameters. Moving the art of lapping into a science and quantifying the results can solve many of the above problems.

In this research, a portable mechanical lapping tool was designed and tested along with manual lapping. Lapping processes were studied by conducting designed experiments, literature search, and consulting experts. The results from the experiments were explored in detail using various statistical techniques to explain the relationships among potential parameters and to see the possibility of lapping model development. A preliminary intelligent computerized lapping system (advisory system) was also developed as a framework for future work. Representative qualitative models and rules for lapping were proposed based on lapping literature and lapping experts' knowledge. However, it was found that the domain knowledge obtained from different sources was often clouded by imprecision and uncertainty, and the available data of manufacturing problems were frequently imprecise and incomplete. To overcome this problem, fuzzy logic concepts were applied in developing a protocol for the knowledge-based system. This research is an initiative of well-designed experiments and data analyses in investigating potential parameters of flat surface lapping with an application on reconditioning valve discs and nozzle seats.

Descriptors

Advisory System

Factorial Design

Flat Surface Lapping

Fuzzy Logic

Knowledge-based System

Nozzle Seat Reconditioning

Rule-based System

Valve Disc Reconditioning

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# 1.0 INTRODUCTION

Lapping is a finishing operation using fine abrasive grit, applied between a lapping block and workpiece. It provides major refinements in the workpiece including extreme accuracy of dimensions, correction of minor imperfections of shape, refinement of surface finish, and a close fit between mating surfaces. Lapping can be used to process virtually every shape of workpiece, i.e. flat surfaces, outside/inside cylindrical surfaces, ball surfaces, double-curved surfaces. However, flat lapping is the most widely used application and, hence, is the main focus of this research. For simplicity, from this point on through out this document, “flat lapping” will be referred to as “lapping”.

The process of lapping has been long considered an art with a tremendous amount of variability and subjectivity involved. Many people still have the image of the lapping process as a skilled person patiently performing the operation on parts one at a time. The lack of complete knowledge of the lapping process is being faced now by many industries, and often prevents lapping from being employed over a considerably wider set of applications. Since lapping has always been considered an art rather than a science, trial and error still serve as the iterative methodology of the process. The quality of lapping differs from operator to operator and the results are highly inconsistent. The material removal rate, surface finish, and flatness all depend on the proper control of lapping parameters such as lapping pressure, lapping speed of rotation, lap ring material, weight and size, abrasive size and type, workpiece material and hardness. To attain the desired outcomes, it is imperative to select proper values for the lapping control parameters. Also there are no established rules or standards for lapping that can provide general guidelines and help select the lapping parameters that are critical to the quality of lapping. As there is no established procedure for determining those critical parameters, these values are often determined using guesswork and experience. Thus, there is no way for the novice operators to acquire important lapping guidelines. They typically learn through years of experience, and, sometimes, mistakes.

Moving the art of lapping into a science and quantifying the results can solve many of the above problems. The following tasks were completed. Lapping valve discs and nozzle seats was selected as a focus for this research. Lapping processes were studied by conducting well-designed experiments, literature search, and consulting experts. The results were thoroughly explored. The relationships among potential parameters were investigated for explanation and the possibility of development of a robust model. Lapping qualitative models, rules, and guidelines were proposed based on lapping literature and the expertise of the lapping operators. Based on this information, a preliminary intelligent computerized lapping system (advisory system) was developed as a guideline for further research in the field. Once completed, the system can help a semi-skilled lapping operator lap parts to the highest quality, in the most efficient and economical way. However, the domain knowledge obtained from manufacturing engineers is often clouded by imprecision and uncertainty, and the obtained data of manufacturing problems are frequently imprecise and incomplete. To overcome this problem, fuzzy logic concepts were applied in building the protocol for the knowledge-based advisory system.

## 1.1 Problem Statement

According to the National Institute of Standards and Technology (NIST), due to the inherent physical complexity of manufacturing processes, process development is often ad-hoc and empirical. Process parameters are typically chosen by costly, trial-and-error prototyping, with the resulting solutions often sub-optimal. In addition, a recent survey by the Kennametal Corporation dramatically demonstrates that U.S. industry chooses the correct tool less than 50% of the time, and uses cutting tools to their rated cutting speed only 38% of the time. These sub-optimal practices are estimated to cost U.S. industry $10 billion per year. Pressure from international competitors is driving industry to seek more sophisticated and cost-effective means of choosing process parameters through modeling and simulation. Optimal manufacturing performance requires sufficient understanding of the impact of individual parameters on the various levels of the control hierarchy.(1) * Potential lapping users are among those who face such problems.

The lapping process was first invented during the prehistoric period and has remained a manual operation for thousands of years. Conventionally, lapping is characteristically an operation for generating ultra-fine finishes, extreme flatness, and critically close tolerances by means of loose-grain abrasives. Distinct from other final finishing processes, lapping has been considered as an art more than a science, because of its highly stochastic nature. The process of lapping has traditionally been performed

* Parenthetical references placed superior to the line of text refer to the bibliography.

without any hard and/or fast rules to follow. Each operator typically iterates multiple times to find the proper combination of parameters that include, but not limited to, the parameters related to abrasives, vehicles, lap rings, workpieces, techniques, tools, and customer's requirements. However, in today's industry, lapping is being used in a variety of applications by manual, mechanical, and automated means. The current problems with which users in the lapping industry are concerned include:

- Naturally, the outcomes from manual lapping are inconsistent due to human errors. There is a need for the development of a lapping tool that will mechanize the lapping process and make it more consistent. The need for a mechanized lapping tool was also realized by United State Products Co. while conducting business in abrasive compounds with the valve manufacturing and reconditioning companies from around the world. The lapping tool is intended to be used in place of manual lapping for on-site valve repair.
- Lapping (both manual and mechanical) involves many interrelated qualitative and quantitative parameters such as material nature of the workpiece and lap ring (plate), type of abrasive mixture, weight of lap ring, pressure, speed of rotation, etc. Without a clear understanding of the relationships among potential parameters, the operator faces difficulty in selecting an optimal combination of lapping techniques and the parameters to achieve the requirement.
- Applied lapping processes have long suffered from the lack of a large-scale computerized knowledge base and are a major deficiency in the body of knowledge.

A protocol for building a lapping advisory system will serve as a meaningful guideline and an initial base for further developing the advisory system.

- Lapping process control parameters are always defined using ‘linguistic’ terms, such as “around”, “about”, “approximately,” which are difficult to be quantified. In addition, multiple combinations of process control parameters often give similar outcomes. Fuzzy logic concepts can be used to overcome such problems in building the advisory system.

## 1.2 Hypotheses

The primary hypothesis of this research is that a protocol for an advisory system, which sets the framework for the implementation of a more comprehensive computerized process planning system, can be developed for flat lapping by embedding rules developed from the results of well-designed experiments and the knowledge of skilled operators and experts. A secondary hypothesis is that qualitative models, proposed based mainly on expert opinion and concepts from the literature review, can logically represent relationships between potential input and output variables for rule-based system development.

## 1.3 Research Focus and Objectives

This research focuses on the analysis of data obtained from a set of designed experiments on manual and mechanical flat lapping with specific applications to valve discs and nozzle seats. The results of the experiments were thoroughly explored and explained to reveal relationships among potential parameters and to investigate the feasibility of developing process control parametric models. Then, using the information from experts and literature search, a protocol for building a knowledge-based system for flat lapping with applications on valve discs and nozzle seats is proposed. The following key elements were gathered, studied in detail, and summarized: (1) basic knowledge and principles of lapping operations (2) problems that are common in the flat lapping process (3) specific concepts of lapping valve discs and nozzle seats.

The principal objectives of the proposed research are:

1. A study of the parameters involved in flat lapping and their theoretical relationships to determine the critical process parameters through ongoing literature review and solicitation from a group of experts. The parameters under consideration are related to abrasive, lap ring/plate, workpiece, technique, and customer's requirement.
2. A set of carefully designed experiments on manual and mechanical lapping with applications on valve discs and nozzle seats to study the behavior of selected potential lapping parameters and to see the possibility of lapping model development.
3. Finally, a preliminary advisory system for advising and process planning for flat lapping with applications on valve discs and nozzle seats is proposed as a guideline for future research.

## 1.4 Anticipated Contributions

The major impact of this proposed research will be in the field of lapping valve discs and nozzle seats, with a secondary impact in the area of computerized advisory systems. Anticipated contributions of this research include:

1. Results of a thorough study of potential lapping parameters by conducting a set of well-designed experiments and statistical data analysis. The result illustrates the behavior of and the relationships among the potential parameters.
2. Development of initial models and rules representing relationships between potential input and output parameters for the flat lapping process advisory system. These models and rules display the roles of key parameters involved in the lapping process.
3. Development of a preliminary computerized lapping system that will standardize the lapping process and make the process outcomes more consistent. The protocol will provide a sound guideline for developing a more comprehensive system that will be able to capture the expertise of expert lapping operators in the form of best lapping procedures or standardized process rules and act as the training vehicle for the novice lapping operators.

In sum, the main contribution of this research is to provide findings and guidelines as a result of a well-designed extensive study.

# 2.0 BACKGROUND AND LITERATURE REVIEW

## 2.1 Lapping Background

### 2.1.1 Process Definition

Lapping is a gentle, final operation commonly used with low speed and low pressure to generate ultra-fine finishes, extreme flatness or roundness, and critically close tolerances. Many researchers have suggested definitions of lapping process. However, the usual definition of lapping is the random rubbing of a part against a lap (usually of cast iron composition or another material that is softer than the part) using an abrasive mixture in order to improve fit and finish.[2] Conventionally, the process of lapping is completed by applying loose abrasive between the surface of the workpiece and tool, without positive guidance of the workpiece and usually resulting in a finish of multi-directional lay. The capabilities of lapping are numerous. However, lapping is most widely used for finishing flat surfaces, which is the main focus of this research. Flat lapping may be done for four reasons, any one of which may dictate the use of the process. The following are basic objectives for lapping:[2,3,4]

1) To obtain an extreme flatness on the order of one to four light-bands[1] (11-44 millionths of an inch) which no other process can match.
2) To obtain a surface finish (roughness) in the range of 0.5-3 micro-inches without difficulty. Thus, lapping can do much to eliminate wear in parts that slide together.
3) To obtain extremely close dimensional tolerances (to 25 millionths of an inch), resulting in a close initial fit between mating parts with the proper clearance for correct lubrication.
4) To obtain minor correction of piece-parts by removal of damaged surface and subsurface layers that degrade the electrical or optical properties.

The most intriguing aspect of lapping is the use of loose abrasive particles. With the possible exceptions of abrasive flow machining or abrasive water jet cutting, no other abrasive machining can claim this distinction.[(3)] The unrivaled ability to produce extremely smooth (upto 0.5 $\mu$-inch) and flat (upto 1 lightband) surfaces is what makes lapping unique.

The following Figure 1 shows surface finish comparison that can possibly be achieved with different manufacturing processes.

[1]Light bands are formed by using an optical flat and a monochromatic light source represent an accurate method of checking surface flatness.

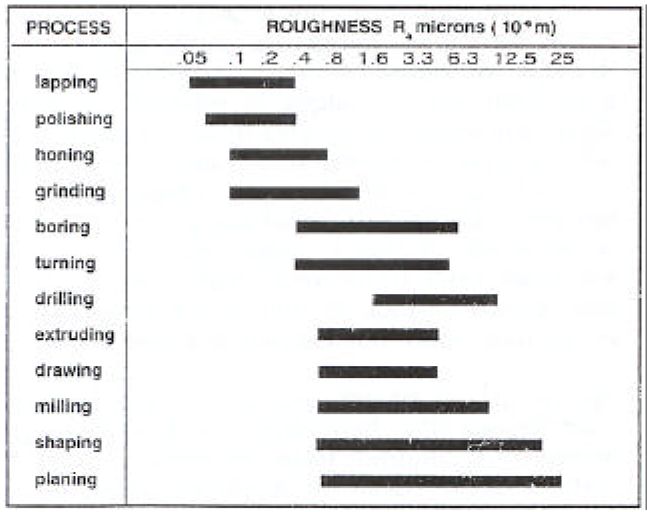



Figure 1 Typical process roughness[3]

Lapping has long been considered an elusive art. It is entirely conceivable that two equally competent operators could arrive at equally good results by utilizing two different techniques and combinations of process-control parameters.

### 2.1.2 Origin and Development of Lapping Process

To appreciate how modern lapping technology evolved, it is necessary to return to the stone age. It was found (by our prehistoric ancestors) that their arrowheads could be made smoother if they were rubbed with wet sand against a smooth rock.[5] A. W. Stahli pointed out that our pre-historic ancestors were among the first to develop lapping to make tools and implements.[3] Figure 2 illustrates a primitive lapping machine.

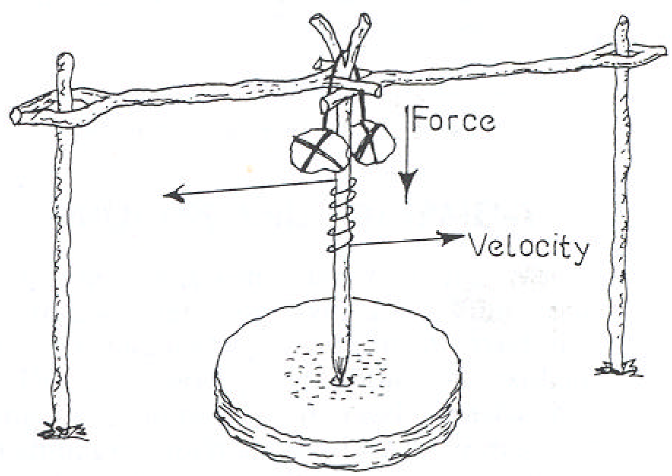



Figure 2 Primitive Lapping Machine[3]

The simple rotation of a weighted stick in close contact with beach sand strewn on a stone *laps* a hole in the stone, (some would assert that this is a first generation drill press or grinding machine). This sketch has originally taken from a model at the German Museum, Munich, and is based on archaeological findings. For thousands of years lapping remained a manual operation, and the image of a skilled man patiently tracing figure-eights while he finished parts one at a time has remained in the minds of many potential users. It prevents them from seeing the possibilities of the process for their operations.[5]

### 2.1.3 Types of Lapping

Lapping can be categorized using different criteria. However, the following criteria are the clearest and suitable for flat lapping. Lapping operations usually fall into one of two categories: individual-piece lapping and matched-piece lapping:[2,14]

1. Individual-Piece Lapping

A special tool called a "lap" is used for this lapping category. The mechanism of this process is that abrasive is rubbed against the workpiece with a lap usually of material softer than the workpiece, rather than with a mating workpiece surface. Individual-piece lapping is usually used to produce optically flat surfaces, produce accurate planes, and to finish parallel faces. The primary concentration in this research will be individual-piece lapping.

2. Matched-Piece Lapping

Matched-piece lapping is sometimes called "equalizing". The mechanism of this process is that two workpiece surfaces separated only by a layer of abrasive mixed with a vehicle are rubbed against each other. Each workpiece drives the abrasive so that the grit particles act on the opposing surfaces. This process will eliminate irregularities that prevent the surfaces from fitting together precisely. However, in many cases, a part is first lapped individually and is then mated with another part by this method, before the two are stocked as a pair of lapped-together parts.

### 2.1.4 The Principles of Lapping Operation

Lapping is an abrasive finishing process and is unique in its cutting action compared to other forms of machining. The basic idea of abrasive finishing is to use a large number of multipoint random cutting edges for effective removal of material at smaller chip sizes than those in the finishing methods that use cutting tools with defined edges.(6) Basically, a workpiece or a lap plate/ring is pressured against a film of abrasive compound that is continuously dripped (or pre-applied) onto the rotating lap plate/ring or workpiece respectively. Another key characteristic of lapping is that it is a low-heat operation. The motion is slow; and there is always the oil or vehicle between the work and the lapping plate. This results in significantly less heat distortion than in grinding.(4)

The abrasive grains mixed with a vehicle (abrasive compound) can be a variety of shapes and sizes. Each loose abrasive grain that comes in contact with the workpiece acts as a microscopic cutting tool. There are three components of abrasion occurring during the process, depending on the shape of the abrasive grain and the composition of the lap plate surfaces.(7,8) Larger abrasive particles tend to “roll” or “slide” between the lap plate and the workpiece, while small particles become “embedded” in the surface of the lap plate/ring (that usually is softer than the workpiece). In other words, the three components of abrasion in the lapping process are:(6,7,8,12)

1) Rolling

The sharp edges of the grains are forced into the workpiece surface and either make an indentation or cause the material to chip away microscopic particles. Figure 3 shows the rolling movement of abrasive grains in a lapping film. As the workpiece moves at velocity (v), the adherent vehicle (liquid) moves with the workpiece. However, the velocity of the liquid at the lapping plate is zero. Ideally, a distribution of velocity with a gradual transition would develop and be disturbed by the abrasive grains contained in the lapping compound. Vortices, which develop in the liquid, pick up and upright the even grains that are lying flat. These grains are thereby forced to do the abrasion as well.

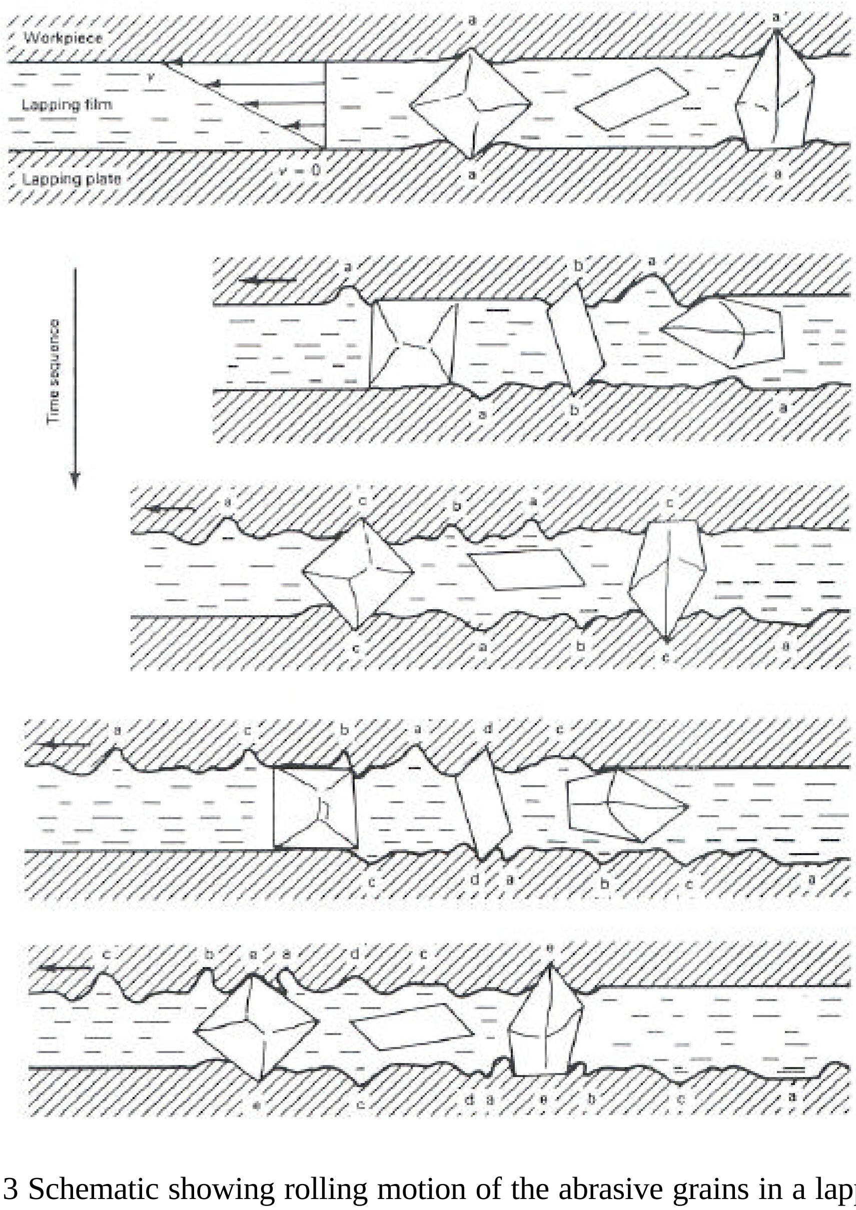



Figure 3 Schematic showing rolling motion of the abrasive grains in a lapping film(8)

2) Sliding

The conditions for sliding are similar to those of rolling. The difference is that sliding occurs for abrasive grains that are more flat or plate-like in configuration. It simulates the cutting action of tiny scrapers as shown in Figure 4. The plate-like abrasive grains are believed to stack on top of each other (similar to tipped-over dominos), thus providing many cutting edges to scrape away the workpiece surface.

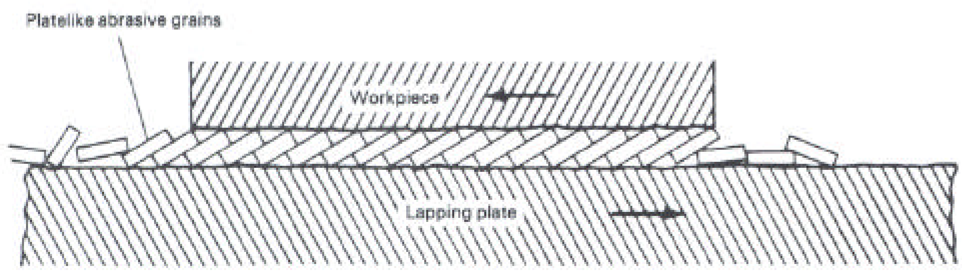



Figure 4 Schematic showing cutting action of plate-like abrasive grains as the grains slide and scrape the region between the workpiece and the lapping plate[8]

3) Embedding

The abrasive grains that are doing most of the work become embedded and act as microscopic scraping tools. These abrasive grains eventually dull or break into fresh sharp grains. The larger abrasive grains that embed in the lap plate provide the most aggressive lapping action when a relative motion takes place between the workpiece and the lapping plate. As these larger grains are worn down or break down, the smaller grains start to embed and also to work. The following Figure 5 shows the cutting action via embedded abrasive grains.

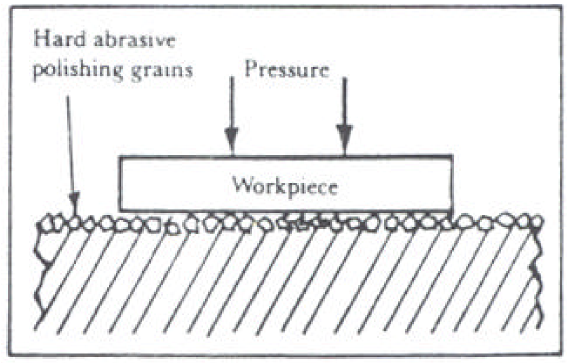



Figure 5 A sketch of hard abrasives embedded in a lapping plate[7]

All of the previously mentioned components of abrasion normally occur together and produce microscopic chips that are small compared to those typically generated in turning, grinding or milling operations.

2.1.5 Abrasive Used in Lapping

Lapping is a high-precision abrasive finishing process.[6] The main characteristic of the process is that abrasive grain entrained in a liquid vehicle (slurry) is guided across the surface to be lapped and backed up by a lapping plate or ring. Thus, abrasive plays an important role as a cutting tool in lapping. The abrasive grains used for lapping have sharp, irregular shapes, with each grain backed by a lapping plate or ring. When a relative motion is induced and pressure applied, the sharp edges of the grains are forced into the workpiece material to abrade away microscopic particles.[7] After applying large quantities of abrasive grains that are irregular in size and shape, the cutting action then takes place continuously over the entire surface of the workpiece. In other words, the cutting action is caused either by rolling grains, platy abrasive sliding rather than rolling, or by abrasive grains imbedded in lap plates that cut more like a tool.[6,7,8,9]

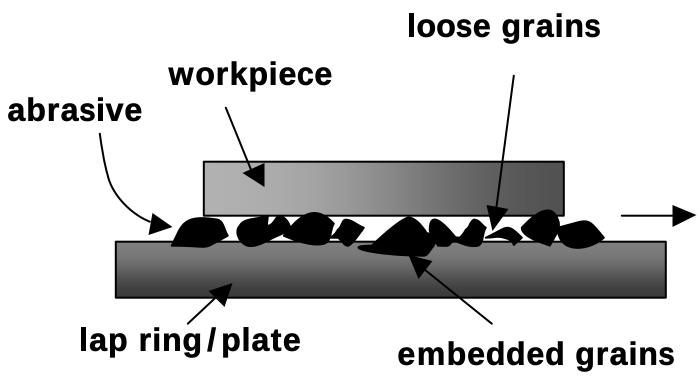



Figure 6 The Abrasion in Lapping

Abrasives come in a wide variety of forms: soft to hard, strong to brittle, coarse to fine, uniform to irregular. They are either natural or artificial crystalline forms. The size and shape of abrasive grains have an effect on the lapping action.[5,8,10] A broad size distribution may cause scratches and be slower cutting than an abrasive grain with a tight size distribution.[8] Hence, the abrasive used in lapping must be very carefully graded for size.[5] Table 1 and 2 respectively illustrate types, hardness, and grit sizes of abrasives that are common in lapping.

Table 1 Lapping Abrasive Type And Hardness[10]

| ABRASIVE | Hardness (MOHS) |
|---|---|
| Diamond | 10 |
| Borazon CBN | 9.7 |
| Norbide, boron carbide | 9.1 |
| Crystolon, Silicon Carbide | 9 |
| Alundum, Aluminum Oxide | 9 |
| 38 White Aluminum Oxide | 9 |
| Fused Alumina | 9 |
| Corundum | 9 |
| Garnet | 8-9 |
| Quartz | 7 |
| Unfused Alumina | 5-7 |
| Linde Powers | ≈ 9 |
| Red Rouge (Ferric oxide) | 6.5 |
| Green Rouge (Chromium oxide) | 8.5 |

Table 2 Average Particle Size Of Abrasive Grain [10]

| Grit Size Number | Inches | Average Microns |
|---|---|---|
| 100 | .0068 | 173 |
| 120 | .0056 | 142 |
| 150 | .0048 | 122 |
| 180 | .0034 | 86 |
| 220 | .0026 | 66 |
| 240 | .00248 | 63 |
| 280 | .00175 | 44 |
| 320 | .00128 | 32 |
| 400 | .00090 | 23 |
| 500 | .00065 | 16 |
| 600 | .00033 | 8 |
| 900 | .00024 | 6 |
| 1000 | | 5 |
| 1200 | | 3 |

Abrasives used in lapping usually are in the form of abrasive slurries or compounds (pastes)[7], i.e. an abrasive is immersed in a binder carrier. The abrasive serves as the principal cutting medium; the binder provides lubrication, prevents overheating of the work, and, in some cases, firmly cements the abrasive to the wheel face or lapping plates/rings. Abrasive slurries are similar to compounds, except that the percentage volume of the carrier fluid is large, providing fluid flow properties to the slurry. Increasing or decreasing the particle size of the abrasive or varying the amount and types of lubricant used in the binder can alter the action of any individual compound. There is no hard/fast rule to follow and each operator must experiment to find the proper abrasive compound.(2,5,10,11,12) The rules of thumb for abrasive compound selection are: (1) the abrasive in a compound should be as hard as (or harder than) the material being lapped (2) a non-embedding or non-charging compound should be used for soft metals (3) if a more intense cutting action is required of a given compound, the particle size of the same abrasive may be increased (4) the softer the metal, the softer the abrasive need, the reciprocal is also true.(10,13)

### 2.1.6 Process Capabilities

Parts that are processed by lapping are constructed from a variety of materials, ranging from metal parts for tooling, gauging, or sealing to electronic crystals such as silicon semiconductor material for integrated circuit manufacture.(2) Tungsten carbide, ceramic, and glass components; aluminum computer disks; tool steel slitter blades; saw blanks; and jade decorative tiles are among the applications that demonstrate the diversity of the lapping process.

Tools and methods have been devised for lapping virtually every shape of workpiece on which a lapped surface is desired. There are two basic methods that can be performed in lapping: hand lapping and mechanical lapping.

1. Lapping with hand-held tools is the oldest method. It is a tedious operation requiring considerable skill on the part of the operator. To obtain consistent and accurate results, highly skilled operators are required.[2,5,7,11,14] The process can be done on flat, cylindrical, and internal surfaces.

2. Mechanical lapping includes a number of machines and methods. It produces accurate, smooth surfaces in large quantities and at high rates of production. Mechanical lapping provides superior quality, in terms of material removal rate, surface flatness, and parallelism to that obtainable by hand methods. However, process controllable parameters need to be well defined to obtain the consistency of the desired results.[2,3,4,9,15,16,17]

Generally, the lapping process can be applied to balls, rollers, cones, double-curved surfaces, assembled bearings, and shapes. However, lapping is most commonly used for fine finishing flat surfaces.[2,4,7,11]

Flat surfaces can be lapped by either manual or mechanical methods. The reasons for flat lapping are numerous. Typically, flat lapping yields accuracy and straightness within 20 micro-inches. However, as many surfaces can be finished to 2 or 3 micro-inches without difficulty, lapping does much to eliminate wear in parts that slide together.[11] Furthermore, as tolerances to 25 millionths of an inch can be held readily, mating parts can be made to fit initially with the proper clearance for correct lubrication.

Reconditioning valve discs or nozzle seats is one of the most important applications of flat lapping. The following sub-section further elucidates this application.

### 2.1.7 Reconditioning Valve Discs and Nozzle Seats

The safety relief valve is a critical component to many process industries, such as chemical, power generation industry, petrochemical, and oil refining industries. Once a safety valve begins to leak, it will continue to do so until it is repaired. Leaking valves can be costly to a company in lost steam or product, with potential fines for polluting the environment, in damaged property or, worse, in the injury and death of workers.(13) An average oil refinery, for example, will have 10,000 valves costing $2,000 or more apiece. Thus, valve reconditioning and refurbishing are extremely important activities for these process industries.

Vital to pressure and safety relief valve repair is the condition of the seating surfaces, the discs, and the nozzle seats. Industries recondition valve discs and nozzle seats using the lapping process, provided that the seat is not seriously damaged. Good seating surfaces must be obtained when reconditioning relief valves. Poor valve lapping will plough, scratch, and round the edges of the valve seats and the discs costing 40-50% of the valve. In addition, poorly conditioned valves lead to an increase in energy expenditure, increased downtime and serious accidents. The following Figure 7 illustrates the positions of the valve disc and nozzle seat in a valve.

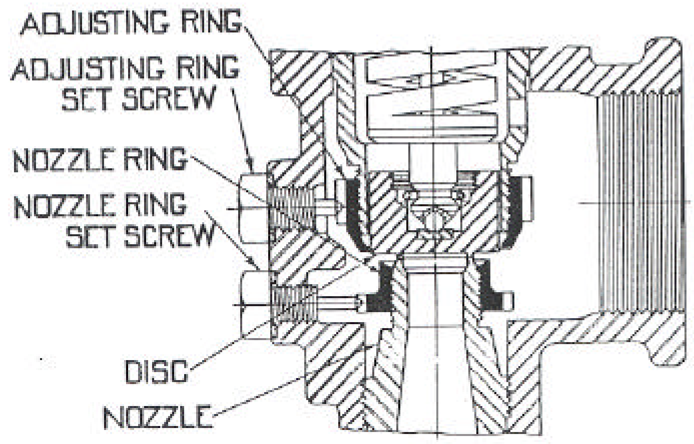



Figure 7 Cross-Section Of A Safety Valve Showing the Positions Of Valve Disc And Nozzle[18]

The tightness of the discs and nozzle seats needs to reach the requirements established by the American Society of Mechanical Engineers (ASME).[13] To achieve the highest possible outcome from flat lapping, operators have to undergo the appropriate selection of process control parameters and procedures. However, most lapping operators typically use their experience and judgment with a trial and error approach as standard procedure for lapping valve-seating surfaces. A detailed process study and computerized advisory system would be helpful for properly trained, qualified, personnel and to repair pressure relief valves.

## 2.2 Lapping Research

While research in lapping has flourished in the fields of material science and tribology, little has been done to clearly explain the relationships of the interwoven potential parameters, especially in flat lapping processes in general. The recent efforts have mostly focused on study the microstructure of non-tradition workpiece materials and specific types of abrasive grain, as well as techniques for lapping unusual-shape workpieces. Some examples of efforts in such fields are summarized here.

Many researchers have studied lapping process with applications to specific workpiece material, e.g. ceramics, quartz, optical lenses, and wafers. Indge[12] introduced general concepts of lapping ceramics with focuses on different abrasive grains (types and sizes) and different types of lapping machine. Chen, Sakai, and Inasaki[19] conducted experiments on lapping ceramics using a special designed lapping machine. Spur and Sabotka[20] studied lapping mechanisms of non-oxide ceramics versus metallic material in terms of compositional structure of both workpieces and abrasive grits. Guzzo and De Mello[21] studied the effect of crystal orientation on lapping natural quartz and found that the relationship between material removal rate and stress existed and that the roughness of the lapped surface decreased with increasing normal stress. Farsakoglu, Kocabas, et. all[22] studied lapping large diameter lens by applying the concept of lateral fracture to examine the influence of optical glass material parameters on removal rate and surface roughness for lens manufacturing conditions. Zhong[23] investigated lapping aspheric and spherical glass surfaces and found that the parameters that helped identify and solve problems in manufacturing were surface roughness, micro-fractures and ductile streaks on glass surfaces. Tomoda and Sugawara[24] studied the effect of caption surfactant properties on glass lapping by conducting a limited number of experiments. The results confirmed that the silver surface possesses high wear resistance irrespective of the lapping apparatus and the specific abrasive grain used. They also found that the high wear-resistance of silver is attributed to adhesion of minute powder particles. Lambropoulos, Su, and Tong[25] applied concepts of surface cracking to explain the fracture roughness into the interpretation of optical glass lapping hardness. Chandler, Lari, and Sudarshan[26] outlined the general procedures for deducing the total lapping time for the preparation of silicon carbide wafers. Jian and Liu[27] introduced the lapping technique of an Indium Phosphide single crystal wafer based on their experiments under pre-designed lapping conditions. Zhang et. all[28] investigated subsurface damage in silicon wafers after lapping operation.

Lapping balls and gears are also among the most widely interested research applications of lapping process. Many researchers have studied and investigated lapping applications to understand and improve lapping technique for such applications. Kang and Hadfield[29] used Taguchi methods to optimize lapping parameters for finishing advanced ceramic balls. Ichikawa et. all[30] proposed a new lapping method for ceramic balls by focusing on lapping pressure, wear distance ratio, mesh number of abrasive sheet, and spherical of balls. Goto and Mizumoto[31] analyzed the influence of the groove depth of lap plates on the waviness of balls in lapping of steel balls. Kurobe, Kakuta, and Onoda[32] proposed an efficient lapping method of silicon nitride balls. Bai, Zhang, Yao, and Wang[33] studied the mechanism of the involute-gear lapping. Mizuno et. all[34] studied compound gear lapping to increase a certain degree of accuracy and roughness of tooth surface. Plotnikov and Belgorodskii[35] investigated and introduced a process for gear-tooth lapping.

Diamond micron powder is most often used in slurries and compounds for lapping and polishing applications.[36] Thus, many researchers have studied lapping applications using diamond abrasive in particular. Mamalis et. all[37] discussed lapping mechanism of lapping $Al_2O_3$ using diamond abrasive and showed the effects of diamond grit size and of the initial porosity on the surface integrity and the material removal mechanism. Marinescu and Turco[38] conducted surface analysis of alumina workpiece lapped with polycrystalline diamond powders to investigate the influence of contact pressure and abrasive size on the surface profile. The results showed that the amount and action of deformation-controlled and micro-fracture controlled wear differ with respect to contact pressure and abrasive size. Touge and Matsuo[39] described the effect of the motion of diamond grains on material removal rate as well as surface roughness during lapping of Mn-Zn polycrystalline ferrite using diamond abrasives. Some researchers focused their efforts to studying the tribological nature of the diamond abrasive. Pimenov et. all[40] studied the tribological properties of smooth diamond film. Kawashima, Hattori, Orii, and Tochihara[41] described the structures of three types of film: multiplayer, monolayer and composite and the results obtained from applying the diamond film.

As can be seen from the above literature review, research in lapping is limited to specific material types, abrasives, and workpiece shapes. Research in flat lapping in general and with applications on lapping valve discs and nozzle seats are not available for public. Thus, the results from this research will make a major contribution to the field as an initial study of flat surface lapping in general.

### 2.3 Grinding Process Models (as an Analogy to Lapping Process Models)

Lapping and grinding share similarity in many aspects, even though they are two distinct manufacturing operations. Lapping and grinding are classified as finishing process that employs abrasive grains as cutting tools. In both processes, many operating parameters affect the performance of the operations. Many process control parameters that are of concern in both operations are similar in their nature. While research in lapping process modeling has been limited, a large number of grinding process models have been developed so far, usually to address specific aspects of the process. Most existing grinding models describe only partial relationships between process variables and operating parameters (design variables) at best. This is due to the inherent complexity of the process and the number of process variables to be considered simultaneously.(42) A few samples of grinding models, which are related to lapping, are introduced here along with significant findings from some lapping process study.

For grinding models, typical input variables include feed rate, wheel and work speed, dress lead, grinding wheel diameter, type and size of abrasive grits, etc. On the other hand, output variables include metal removal rate, normal and tangential forces, surface integrity, roundness, wheel wear rate, vibration, safety, etc.(42) There might be a large number of grinding models pertaining to surface grinding processes. However, the following seven grinding models have been identified as the most representative and important:[43]

1) Chip model
2) Energy model
3) Force model
4) Surface finish model
5) Stress model
6) Temperature model
7) Safety model

The three models, surface finish, stress, and temperature models, seem to be relevant, if anything at all, to lapping process. Thus, these three models are further explained here.

Surface Finish Model

For the surface finish, the root mean square ($R_g$) value is extracted as a process variable, and the depth of cut is selected as a design variable.[43] A formula to calculate the $R_g$ value of the surface after grinding, derived by Pandit and Sathyanarayanan[44] is shown below.

$$R_g = \frac{A_c - 7.596\left[\frac{F_n^{\,2} A_g W_g^{\,2}}{b^2 D}(K_w + K_g)^2\right]^{\frac{1}{3}}}{\sqrt{2}} \quad \ldots\ldots\ldots\ldots\ldots(1)$$

$R_g$ : rms surface roughness value

$A_c$ : amplitude of the secondary wavelength of the wheel profile

$F_n$ : normal thrust force on the wheel

$A_g$ : amplitude of the primary wavelength of the wheel profile

$W_g$ : wavelength of the primary wavelength of the wheel profile

$b$ : width of cut

$D$ : diameter of the wheel

$K_w$ : are given by $\frac{1-n_w^2}{\prod E_w}$; $\nu_w$ = Poisson's ratio for workpiece, $E_w$ = elastic moduli for workpiece

$K_g$ : are given by $\frac{1-n_g^2}{\prod E_g}$; $\nu_g$ = Poisson's ratio for grit, $E_g$ = elastic moduli for grit

Surface finish is among potential parameters in both lapping and grinding processes. As can be seen from the equation (1), $R_g$ is non-linearly related to many process parameters, mostly due to grinding tool. However, most of these parameters are considered irrelevant for lapping due to different process characteristics, particularly in term of tool used. Thus, further investigation will distinguish lapping from grinding and show relationship between $R_g$ and lapping parameters.

Stress Model

Both grinding and lapping are abrasive-machining processes. It was found that the grain strength strongly depends on particle size. The grain size and the uniaxial tensile strength in the following stress model were chosen as the design and the process variables respectively. [43]

$$s_e = 1001\frac{P}{a^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$\sigma_e$ : the effective uniaxial tensile strength (KPa)

P : the load at fracture (N)

A : the dimension of abrasive grains (mm)

The above stress model in equation (2) is simple and seems to be applicable to lapping process at the first glance. Unfortunately, loose abrasives are used in lapping, while, in grinding, they are fixed to the wheel. The stresses for lapping are also much lower in case of lapping. The investigation of the microstructure of abrasive grit and its effect is, however, beyond the scope of this proposed research.

Temperature Model

Malkin and Anderson(45) introduced the concept of total grinding energy and hypothesized that it could be categorized into the energies generated due to chip formation, plowing, and sliding components. Then the grinding temperature could be calculated from the results of the energy partition. It has been found that the peak local temperature at the cutting edge of an abrasive grain is close to the melting point of the workpiece.(43) By assuming that workpiece burn occurs at a critical grinding zone temperature, Malkin(45) suggested the following temperature models:

$$Q = (9.0*10^{-5})d + (4.1*10^{4})D^{\frac{1}{4}}d^{\frac{1}{4}}V_w^{\frac{-1}{2}} \ldots\ldots\ldots\ldots\ldots (3)$$

$$T_{\max} = 1.595\frac{R_3 q_3}{k}\left(\frac{Kl}{V_w}\right)^{\frac{1}{2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$q_3 = \frac{F_H V_s}{(Dd)^{\frac{1}{2}} b} \qquad \text{……………………………………….(5)}$$

Q : energy flux, energy input per unit area ground

d : downfeed per pass

D : wheel diameter

$V_w$ : workpiece velocity

$T_{max}$ :maximum grinding zone temperature

$R_3$ : fraction of grinding energy to workpiece

$q_3$ : grinding energy rate per unit area of grinding zone

k : thermal conductivity

K : thermal diffusivity

l : semi-length of heat source

$F_h$ : horizontal or power force component

$V_s$ : wheel speed

b : width of workpiece

Temperature plays an important role in grinding because it is a high-speed processing. The significance of temperature decreases dramatically in lapping due to its slow-speed and low-pressure natures. In addition, Chandrasekar and Shaw(46) found that lapping surface temperatures are so low that no thermally induced (tensile) residual stresses are involved.

Though the grinding models discussed in this section are not directly applicable for lapping, they provide directions for further investigation of lapping and its potential parameters.

## 2.4 Expert Systems (Advisory Systems)

By definition, an expert system is an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution.[47] The basic structure of an expert system consists of four major elements as shown in Figure 8:

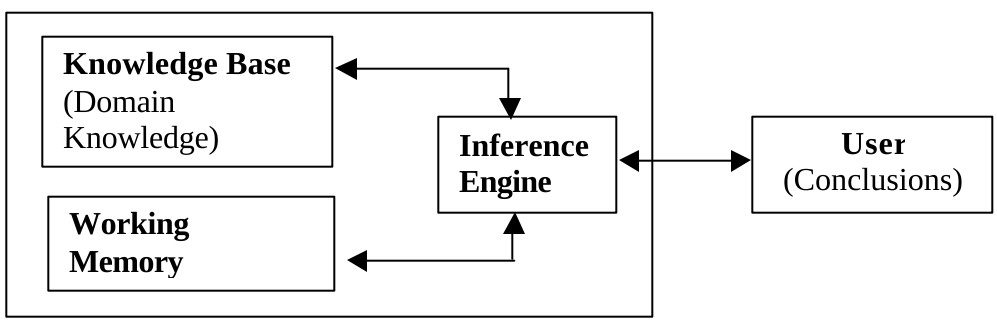



Figure 8 Basic Structure of the Expert System[48]

1. The knowledge base contains domain knowledge (facts) and heuristics associated with the problem.

2. The working memory contains the facts about the problem and the input data for the particular problem that are discovered during the consultation.

3. The inference engine matches the facts contained in the working memory with the domain knowledge contained in the knowledge base, to draw conclusions about the problem.

4. The user interface serves as a link between the user and the expert system.

The existing method of lapping is labor intensive and requires highly skilled operators. Any significant reduction in the setup and correction stages will reduce the unit cost and improve competitiveness in the lapping industry. In order to ensure process reliability and productivity in a highly automated manufacturing environment, it is necessary for such processes to operate intelligently.(49) Hence, to make lapping more reliable and productive, an intelligent system is needed. Over the past several years, advisory systems have begun to be realized on their potential for solving these kinds of problems.(50,51,52) Many manufacturing organizations have now developed hundreds of advisory systems to assist their manufacturing processes.(50,51,53,54) Researchers believe that advisory systems can now provide a high-level design environment that is powerful, supportive, flexible, broad in scope, and readily accessible to non-expert users.(55) The literature contains many references related to both the selection of appropriate applications for advisory systems technology,(56,57,58,59) and the advisory systems building techniques that facilitate the development of the system saving time, money and improving the overall performances of the system itself.(60,61,62)

## 2.5 Fuzzy Logic and Fuzzy Rule-Based System

The kernel of an advisory system is its knowledge base.(63) Although various knowledge representation schemes have been developed for constructing the knowledge base, the most frequently used is the rule-based scheme.(57,63,64,65,66) In a rule-based advisory system, domain knowledge is translated into a set of rules and stored in the knowledge base. For some applications, the domain knowledge acquired from human experts can be expressed in terms of two-valued logic (e.g. true/false). In other words, the information is precise and certain. Under such a situation, a conventional advisory system technique can be used effectively in problem solving.(63,67,68,69,70,71) However, this is not always the case in solving manufacturing problems. The domain knowledge obtained from manufacturing engineers is often infused by imprecision and uncertainty, and the available data of a manufacturing problem are frequently imprecise and incomplete. Hence, the rules in the resultant rule base are often "fuzzy" in nature.(63) This is also the case in the lapping process. Under such a situation, a conventional advisory system technique is incapable of solving problems. The fuzzy set theory has provided advisory system developers with a unified and effective framework for dealing with the "fuzzy" information.(63) The development of a fuzzy rule-based advisory system is becoming increasingly attractive in solving a class of problems containing incomplete and imprecise information.(72,73,74) Recent cross-fertilization between fuzzy set theory and rule-based advisory systems has resulted in successful fuzzy advisory systems.(68,74,75)

Fuzzy logic is the application of fuzzy set theory to the principles of classical logic. Traditionally, logic has been formulated mathematically in terms of

TRUE/FALSE duality also known as bivalent logic. Fuzzy sets were first introduced by Zadeh,[76] and have been applied in various fields. The theory of fuzzy sets and fuzzy logic is well-founded and strong. The theoretical basis behind fuzzy techniques allows us to deal with uncertainty in a manner that is well supported. The theory properly used will allow fuzzy reasoning schemes to be developed and applied to a wide range of problems. The following paragraphs will briefly explain fuzzy set theory.[74,75,76,77]

Membership

Let X be a set of objects whose elements are denoted by x. Membership in a classical subset A of X is often viewed as a characteristic function $m_A$ from X to a valuation set {0,1} such that

$$m_A(x) = \begin{cases} 1 & \text{if and only if } x \in a \\ 0 & \text{otherwise} \end{cases}$$

If the valuation set is allowed to be the real interval [0,1], A is called a fuzzy set, $m_A(x)$ is the grade of membership of x in A. The closer the value of $m_A(x)$ is to 1, the more x belongs to A.

Fuzzy Numbers

A fuzzy number is a real-number fuzzy set that is both convex and normal. Expert systems can use fuzzy numbers to handle fuzziness or imprecision in real numbers and thus to represent and manipulate linguistic terms such as near 0.1 µm, close to 0.2 µm.

Example:

Near 0.1 µm can be represented by fuzzy number (0 0 0.1 0.2)

Near 0.2 µm can be represented by fuzzy number (0.1 0.2 0.4)

Linguistic Variables

A linguistic variable differs from a numerical variable in that its values are not numbers but words or sentences in a natural or artificial language. The following is an example of linguistic variable application:

Example:

Parameter--Initial Surface Roughness (µm)

| Linguistic Variables | Fuzzy Number |
|---|---|
| superfinish | (0 0 0.1 0.2) |
| hi-finish | (0.1 0.2 0.4) |
| finish | (0.2 0.4 0.8) |
| smooth | (0.4 0.8 1.0) |

Aggregation of Fuzzy Rules

The process of obtaining the overall consequence (conclusion) from the individual consequences contributed by each rule in the rule-base is known as aggregation of rules.[77] The followings are two existing extreme cases:

1. Conjunctive System of Rules: In the case of a system of rules that must be jointly satisfied, the rules are connected by "and" connectives. In this case the aggregated output (consequent), y, is found by the fuzzy intersection of all individual rule consequences, $y^i$, where i = 1,2,…,r, as

$y = y^1 \cap y^2 \cap y^3 \cap \ldots \cap y^r$

which is defined by the membership function

$$m_y(y) = \min(m_{y^1}(y), m_{y^2}(y), \ldots, m_{y^r}(y)) \text{ for } y \in Y$$

2. Disjunctive System of Rules: For the case of a disjunctive system of rules where the satisfaction of at least one rule is required, the rules are connected by the "or" connectives. In this case the aggregated output is found by the fuzzy union of all individual rule contributions, as

$y = y^1 \cup y^2 \cup y^3 \ldots \cup y^r$

which is defined by the membership function

$$m_y(y) = \max(m_{y^1}(y), m_{y^2}(y), \ldots, m_{y^r}(y)) \text{ for } y \in Y$$

A fuzzy advisory system is a system that incorporates fuzzy sets and/or fuzzy logic into its reasoning process and/or knowledge representation scheme.(74) Recently, several artificial intelligent techniques, including advisory systems and fuzzy logic, have advanced to the point where they can produce promising results in solving real-life problems.(78) Most of the current activities in developing computer aided manufacturing systems are focused on the expert system approach, in which a knowledge base is built to capture manufacturing logic.(79,80,81) Actually, when constructed properly, a fuzzy advisory system can emulate a human expert in a specific domain, such as process planning/advising. The application of fuzzy logic in engineering has been focused on the area of fuzzy control.(82) Very little literature is available in the application of fuzzy logic in process planning/advising. However, in lapping process planning/advising, some objectives are imprecise in nature. For example, an expert process planner may use his/her own criteria in process plan selection e.g. the cost should be reasonably low, the lapping time should not be too long, etc. Therefore, the application of fuzzy logic is necessary here and will enhance the knowledge of the field. In this proposed research, a fuzzy logic approach will be applied to deal with lapping process planning/advising problems. The application of fuzzy set theory changes the basic foundation of TRUE/FALSE logic by considering partial truth. Because being a member of a fuzzy set is a matter of degree, the observation being TRUE is also a matter of degree. Thus, a statement like "*IF* desired surface finish is SUPER finish" becomes partially true in fuzzy logic. That is, in most cases, a more accurate representation of the reality than that of bivalent logic.

# 3.0 METHODOLOGY

The main objectives of this research are: (1) to study the process of flat lapping with an application on valve disc and nozzle seat reconditioning, (2) to investigate relationships among potential flat lapping parameters, and (3) to develop a protocol for lapping advisory system. In this chapter, the methodology for the first two objectives will be explained. For logical reasons, the methodology in the context of advisory system development to carry out the third objective can be found in Chapter 7.0 in this document.

## 3.1 Design of Prototype Lapping Tool (Mechanical Lapping)

As part of this research, a prototype lapping-tool was developed and tested in comparison to manual lapping. The design focus is on simplicity, portability, and cost effectiveness. The lapping tool is intended to be extensively used where manual lapping is usually being done at the repair site. Naturally, the outcomes from manual lapping are inconsistent due to human errors. There is a need for the development of a lapping tool that will mechanize the lapping process and make it more consistent. The need for a mechanized lapping tool was also realized by the management (primarily the President of the company) of United State Products Co., who has been involved in this research, while conducting business in abrasive compounds with the valve manufacturing and reconditioning companies from around the world.

The prototype lapping tool (PLAT) was designed using the basic design process. The process can be broken down into the following phases: 1) recognition of need for lapping tool 2) definition of lapping problem 3) design & synthesis of components 4) analysis 5) evaluation and 6) documentation and blue prints. See Appendix A for detailed drawings of the lapping tool.

## 3.2 Determination of Critical Process Parameters

The lapping operation inherently involves a great number of parameters, which have direct or indirect influence on the surface integrity of the lapped discs and nozzle seats. However, to be more realistic, pilot studies need to start with identifying the most critical process parameters instead of studying all process parameters. Critical process parameters are those that possess direct influences to the process performance and can be measured or defined. In this research, the critical parameters under consideration were selected from the following three avenues:

1. Rules of Thumb

   This avenue focused mainly on general lapping techniques and tools. Considering lapping techniques and tools used in general provides a framework of lapping parameters that are involved in flat lapping operation.

2. Literature Search

   This avenue focused on findings in recent research of surface engineering and lapping in particular. Though research in flat lapping is limited, studying the results from current efforts in lapping operations provides a broad idea of which parameters play an important role in the lapping operations.

3. Expert Solicitation

This avenue focuses on gathering inputs from experts in the field of lapping. A series of interviews were conducted using a set of pre-designed questions. At times, experts can give insightful information based on their genuine experiences. Their insights can also be used as a practical validation for parameters of interest.

## 3.3 Experimental Design

Experiments are performed by investigators in virtually all fields of inquiry, usually to discover something about a particular process or system. Literally, an experiment is a test. A designed experiment is a test or series of tests in which purposeful changes are made to the input variables of a process or system so that we may observe and identify the reasons for changes in the output response. The process under study can be represented by the model shown in Figure 9.[83]

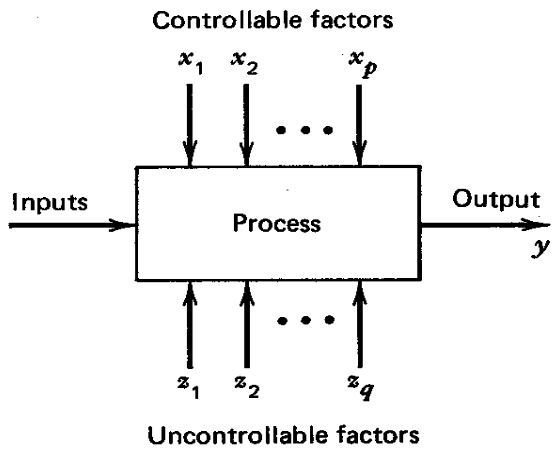



Figure 9 General Model of a Process or System

From Figure 9, it can be visualized that a process transforms some input into an output that has one or more observable responses, based on the values of controllable and uncontrollable variables. Thus, it is critical to study the effects of these controllable and uncontrollable variables, if the more understanding of the process is desired. Experimental design plays an important role in this research since it is a pilot study in the field and so that the meaningful results and conclusions can be drawn.

In this research, the concepts of full and fractional $2^k$ factorial designs was used to investigated possible combinations of the levels of the factors of interest in flat lapping for both manual and mechanical lapping. The factors of interest are those determined as critical process parameters. It is believed that a factorial design is necessary when interactions may be present to avoid misleading conclusions. In addition, factorial designs allow the effects of a factor to be estimated at several levels of the other factors, yielding conclusions that are valid over a range of experimental conditions.

## 3.4 Conducting the Experiments

A series of well-designed experiments for both manual and mechanical lapping were conducted at two valve repair facilities:

1) Anderson Greenwood / Crosby Valve, Inc., Wrentham, MA
2) A-G Safety Sales & Service of Texas, Inc., Baytown, TX

These two valve repair facilities are best known in their manufacturing capabilities and high standards of valve repairing through the process of flat lapping.

## 3.5 Data Analysis

The main purpose for data analysis in this research is to investigate all the effects and relationships among the critical process parameters. Statistical methods were used in analyzing data collected from series of experiments. Due to the unusual nature of the data, the results and findings from data analysis using different statistical techniques were explained and compared to show more meaningful findings from the experiments. The following statistical analysis techniques were used: Analysis of Variance, Non-parametric Tests, Multivariable Regression, and Multivariate Analysis.

## 3.6 Development of Parametric Models

The lapping process has been considered an art because of its highly stochastic nature and involvement of many tentative parameters. In selecting an appropriate combination of these parameters to achieve the highest performance of such process,

process models representing relationship among critical parameters are in need. The stochastic nature and variety of parameters in the lapping process result in complexity of the process model development. In the beginning of this research, one of the objectives was to develop parametric models for flat lapping. However, due to limitations of resources and obtained data, as well as the findings from pilot studies in this research, it was not possible to do so. Instead, the results were explained to provide a broad picture of how critical process parameters are related. In addition, these findings can be used as a starting point for further research in lapping model development. For future research, methods of lapping model development are described below.

### 3.6.1 Identify Potential Input and Output Parameters for the Models

The information obtained from extensive experiments, lapping experts, and other sources of expertise can be used in analysis to evaluate important intuitive relationships of the explanatory variables under study on the response variables. The findings from series of well-designed experiments plays an important role in developing such representative models. The following diagram depicts the analysis process:

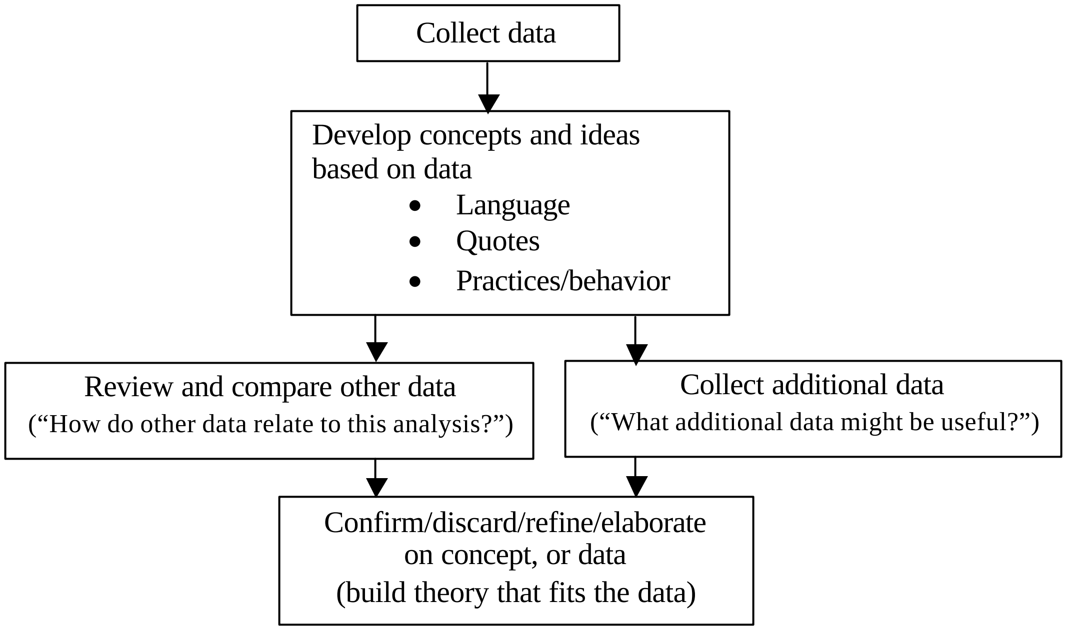



Figure 10 Data Analysis Process (adapted from Taylor and Bogdan[84])

From the results of the analysis, potential input and output parameters for the qualitative models can be identified. Then, the related parameters can be represented in the form of simple models.

### 3.6.2 Qualitative Model Building

Qualitative models can be developed based on the results from statistical analyses of the obtained data from series of experiments and literature search as well as expert solicitation. The concepts gathered from lapping experts and/or other sources of expertise can be integrated into the process of these qualitative modeling. The models and relationship trends can be used to represent relationships among potential input and output parameters. Finally, these models can be consequently used as references for rule-based creation, especially for process planning module.

# 4.0 LAPPING TOOL AND CRITICAL PROCESS PARAMETERS

## 4.1 Design of Mechanical Lapping Tool

The process of designing a lapping tool was carried out via the 6-step basic product design process: 1) recognition of need for the type of lapping tool, 2) definition of lapping problem, 3) design & synthesis of components, 4) analysis, 5) evaluation, and 6) documentation and blue prints. The detailed design process is beyond the scope of this research, however, it has been documented and filed with United State Products Co. For simplicity, the six steps are summarized in this chapter.

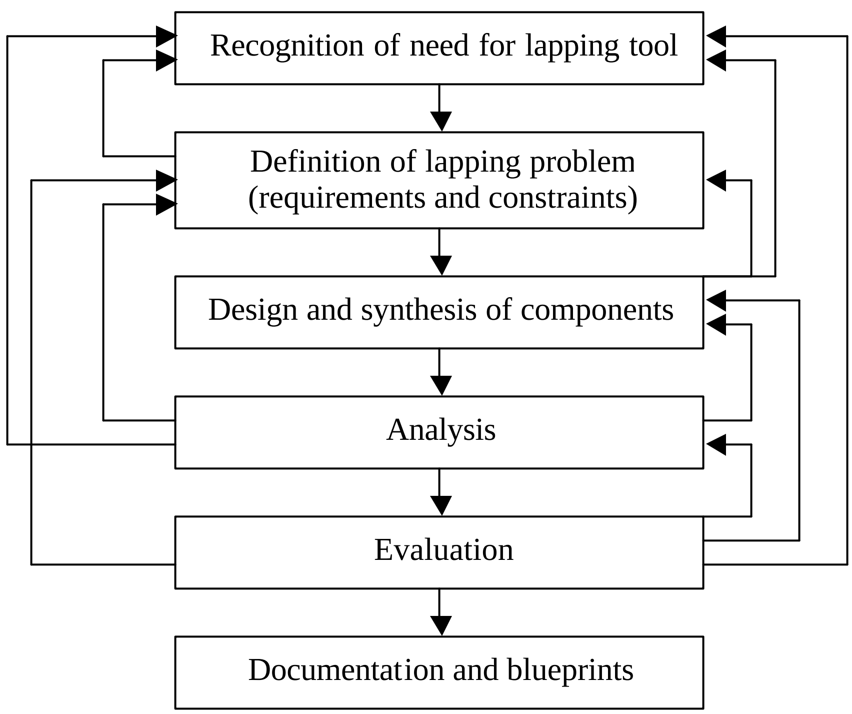



Figure 11 The Phases of Design for the Lapping Tool [adapted from Shigley and Mischke[85]]

The 6-step basic product design process is shown in Figure 11. The need for a mechanized lapping tool was realized by United State Products Co., who has been involved in this research. The main focus of the organization is conducting business in abrasive compounds with multiple valve manufacturing and reconditioning companies from around the world. The main reason for the need of a lapping tool is that most organizations manually recondition valves by applying abrasive compounds with lap rings. Many organizations lack skilled lapping operators, thus, have to send valves out for reconditioning for a high service fee. Further, the manual lapping procedure introduces variability and adversely effects the attainment of tolerances close to two light bands flatness or less. Thus, there is a need for the development of a lapping tool that will mechanize the lapping process and make it more consistent across different workers while reducing the human variability factor in the manual lapping process. The tool should be simple, inexpensive and portable for it to be used extensively in reconditioning valves at the repair site.

The next critical step is the definition of the problem. The lapping tool was conceived to be a portable device, which can be used at the valve site for the repair of damaged valves. Portability would, thus, constrain the tool size in not being bulky and the individual components of the parts being relatively light. Other critical requirements for the tool were that it should be extremely accurate (to ensure flatness) and there should be provision to provide the rotational motion using a mill/drill press or a simple motor while lapping. The tool should also provide for a way to adjust the pressure applied during lapping.

After problem definition, the next step is synthesis. This step consists of the actual design of the various components. The design of the various components was arrived at by considering the need and problem definition carefully, numerous brainstorming sessions, literature review, and consultations with mechanical engineers and machinists.

The next steps of analysis and evaluation were carried out as the synthesis stage progressed. Various components such as the base plate, bearing, the shaft, and the spring were analyzed and evaluated for functionality and adherence to specifications. Thus, the synthesis, analysis, and evaluation were carried out iteratively by continually improving the various component designs and then evaluating them.

The prototype lapping tool was used in this research for mechanical lapping experiments. The results were discussed and compared with those of manual lapping. The following Figure 12 illustrates the mechanical lapping tool. The detailed drawings for each component are in Appendix A.

The functionality of the lapping tool is briefly explained here. The lapping tool, designed as part of this research, can be used for lapping both valve seats and discs. As shown in Figure 12, the tool essentially consists of an upper spring-loaded shaft and a lower rotating plate. As required by the lapping process, the rotational movement of the lap ring and the part being lapped can be provided by rotating the shaft in a drill press or milling machine, or along with rotating the lower plate. The rotation of the ring plate can be achieved automatically by a light pressure from the drill press or milling machine passing through the upper shaft. However, the speed of rotation of the ring plate is usually slower than that of the upper shaft. When lapping a nozzle seat, the nozzle is placed inside the ring plate while the lap ring is attached to the upper shaft. In the case of the valve disc, the disc is attached to the upper shaft and the lap ring is placed inside the ring plate.

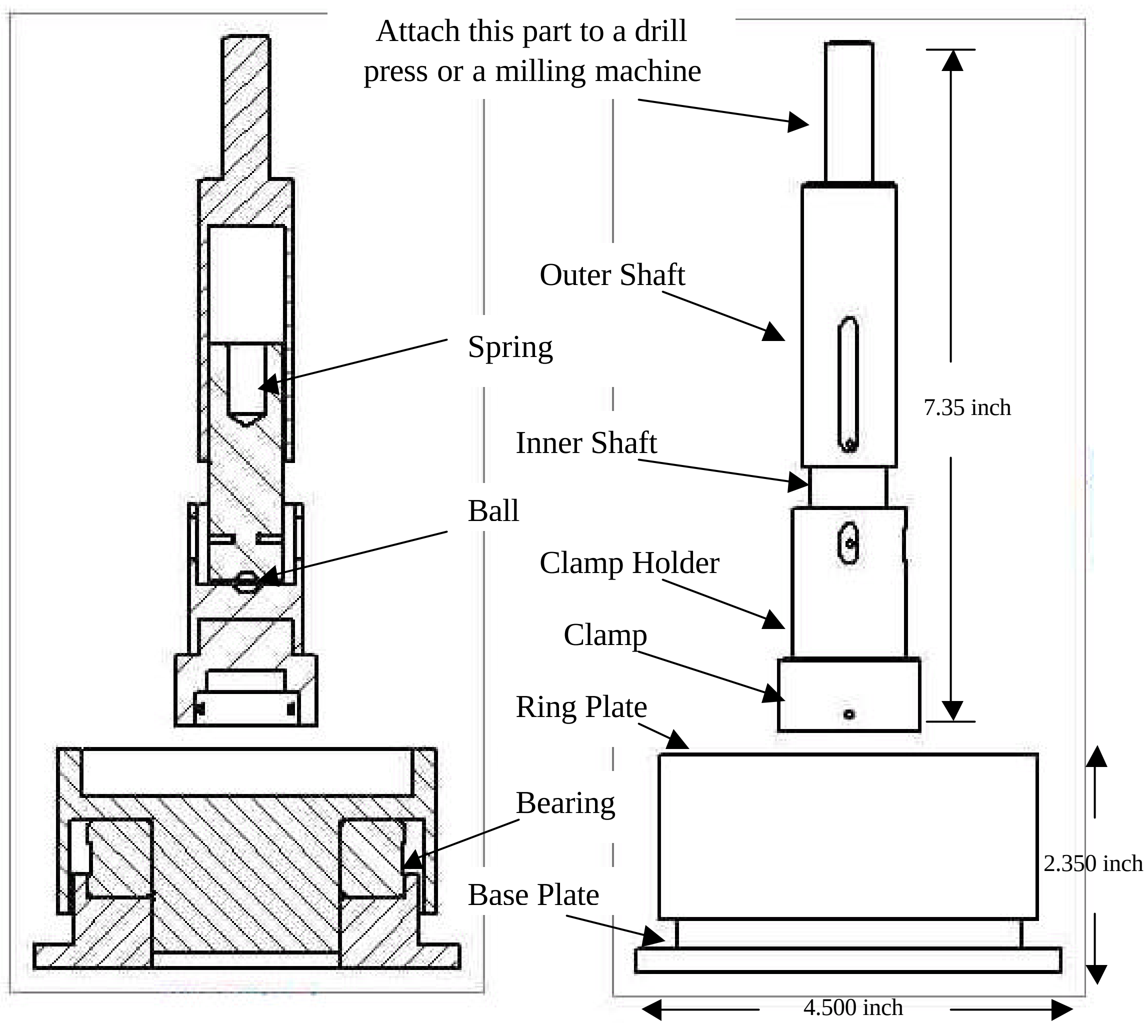



Figure 12 Prototype Mechanical Lapping Tool (sponsored by United State Products Co.)

The lapping process requires the lap ring to apply some controlled pressure to the work piece. The clamp used to hold the lap ring and the disc is an extremely critical component. The clamp has to secure the part, while allowing it to attain its natural seating on the valve seat or the lap ring as the case may be. This is essential to ensure that the lapping is uniform as the tolerances involved are extremely small. The ring plate is separated from the base plate by a thrust bearing that helps in facilitating the rotational motion of the ring plate. The lap ring/valve seat is placed off-center as compared to the valve disc/lap ring on the ring plate to ensure that there is some amount of eccentricity such that the same sector of the lap ring is not repeated each time. This is essential to ensure that the lapping is done uniformly.

It must be noted here that United State Product Co. had embarked on the process of acquiring a U.S. patent for the conceptual design of the lapping tool before this research was initiated. Based on the concepts developed by United State Product Co., this research further refined the design of the mechanical lapping tool and conducted the detailed design of each component of the tool, test, and re-design of the lapping tool. After conducting experiments using the prototype lapping tool, the tool has undergone some re-modification.

## 4.2 Explanation of Critical Process Parameters

The lapping operation involves a great number of parameters that have direct or indirect influence on the surface integrity of the lapped surfaces. Many factors contribute to the difference in quality of outcomes as a result of lapping done by different lapping operators or even from the same lapping operator. As an example, Spur and Sabotka[86] intuitively summarized parameters influencing the lapping operation in general as in the following Figure 13. In this research, some parameters specific to flat lapping valve discs and nozzle seats were selected and used in experiments. The critical lapping parameters were selected by three avenues; 1. rules of thumb, 2. literature search, and 3. expert solicitation. Each selected critical parameter for manual lapping and mechanical lapping is explained in the following sub-sections.

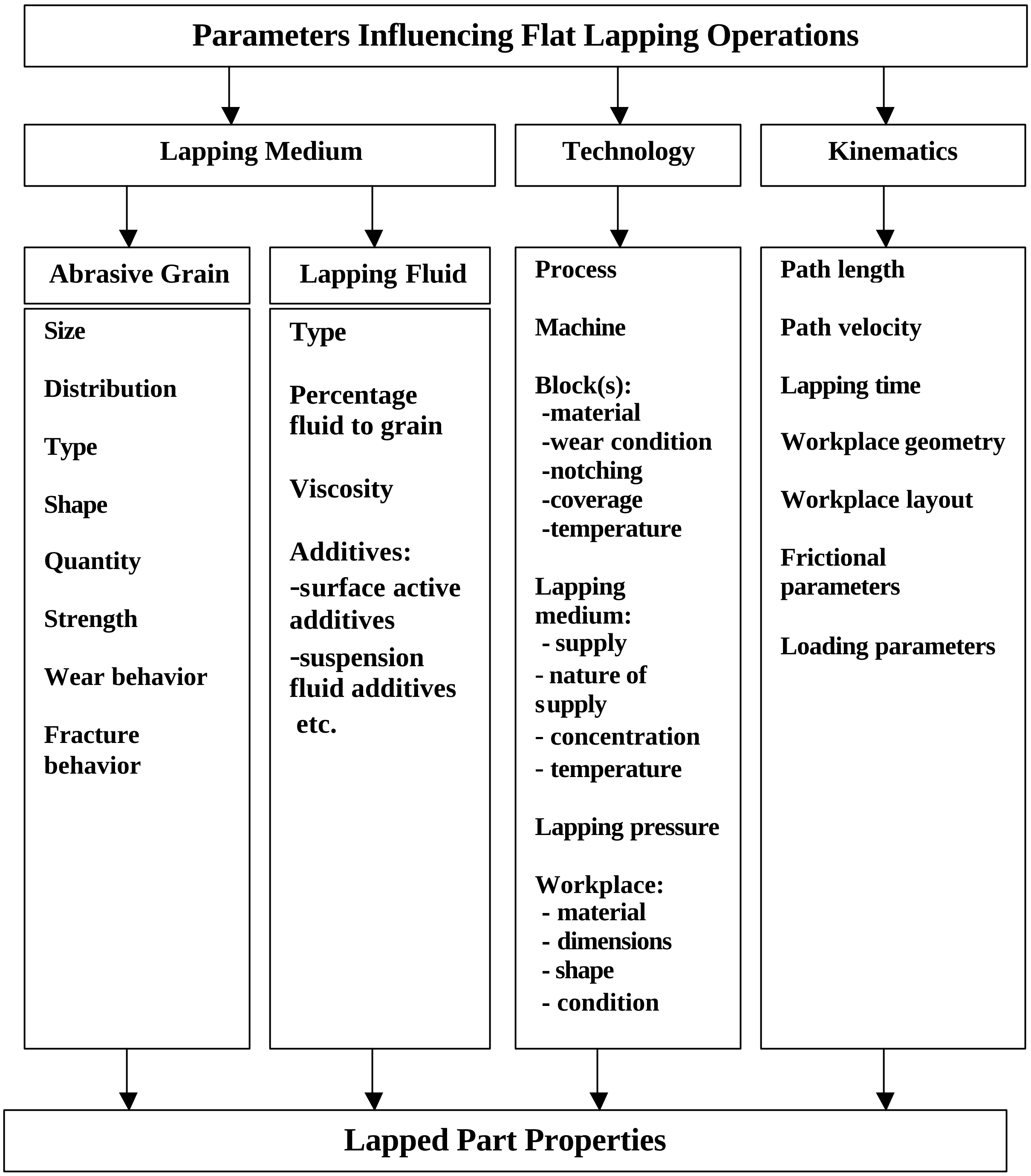



Figure 13 Parameters Influencing the Lapping Operation in General[86]

### 4.2.1 Manual Lapping

- Lapping Pressure (newton/in$^2$)

  - Lapping pressure refers to a vertical pressure passing from lap ring to the workpiece surface. The following Figure 14 illustrates the direction of lapping pressure. For manual lapping, pressure is usually generated from weight of the lap ring and very light compressive force from the hand that holds lap ring.

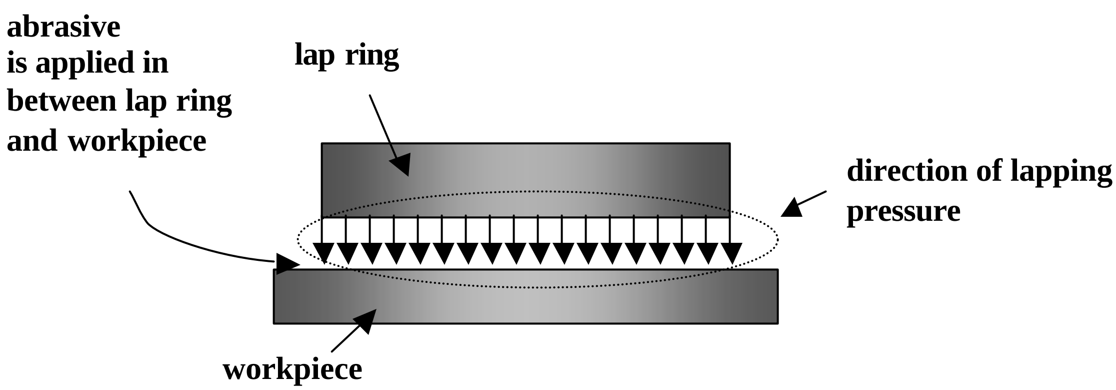



Figure 14 Vertical Pressure Occurred in Manual Lapping

- Abrasive Material (Type)

  - Lapping abrasives are loose grains and either natural or artificial crystalline forms. Abrasives may be differentiated by properties of their grains, which come in a wide variety of forms: soft to hard, strong to brittle, coarse to fine, uniform to irregular. Generally, abrasive materials are classified by the hardness of abrasive grains. The hardness can be measured by indenting the surface with a small indenter made from a harder material. The hardness can then be inferred from the width or area of the indentation or from its depth. Hardness may be presented using different scales such as MOHS, FILE, KNOOP, ROCKWELL C, BRINNELL, and SCLEROSCOPE. Hardness tests are made under arbitrary conditions and there are no basic correlations for converting numbers from one scale to another. The best that can be done is to calibrate one scale in terms of another. The following Table 3 shows an example of comparison among three scales of hardness. More detail on lapping abrasive is explained in Section 2.1.5.

Table 3 A Comparison of Different Scales of Hardness

| | **ROCKWELL C** | **BRINNELL** | **SCLEROSCOPE** |
|---|---|---|---|
| Very Hard | 55 to 68 | 555 to 745 | 75 to 100 |
| Hard | 45 to 55 | 432 to 555 | 59 to 75 |
| Med. Hard | 35 to 45 | 331 to 432 | 46 to 59 |
| Med Soft | 25 to 35 | 255 to 331 | 37 to 56 |
| Soft | 9 to 25 | 183 to 255 | 27 to 37 |

- Abrasive Grit Size (in grit size numbers)
  - Each abrasive type also comes in different grit sizes. If more intense cutting action is required of a given abrasive type, the grit size of the same abrasive may be increased (smaller grit number) or vice versa. Table 2 in Section 2.1.5 shows an example of average particle sizes of abrasive grains.
- Lap Ring Material (type)
  - Lap ring/block is important for lapping operation. The ring/plate should be heavy enough and properly designed so that it will not distort in use. The main function of the lap ring/block is to distribute the abrasive paste or slurry and to drive the abrasive grains, which, in this case, act as multipoint cutting edges by rolling, sliding, or embedding. There are many types of lap ring material. It is a common conclusion that the lap ring/block must be softer than the work, in order that the grains become imbedded in the ring/block.
- Lap Ring Size (diameter or area)
  - Different sizes of lap ring/block may be selected relatively to the sizes of the workpiece being lapped. Lap ring size is critical because it directly relates to lapping pressure. An appropriate selection of lap ring size is required to ensure a desirable outcome from lapping operation.

- Part Material
  - Parts that are processed by lapping are constructed of a variety of materials, ranging from metal parts for tooling, gauging, or sealing to electronic crystals such as quartz piezoelectric frequency devices and silicon semiconductor material for integrated circuit manufacture. The physical properties such as hardness and brittleness also play an important role here. Thus, in lapping, an appropriate selection of process parameters is required for each part material to ensure a desirable outcome.
- Part Type
  - Lapping is capable virtually for every shape of workpiece on which a lapped surface is desired. However, lapping is most widely used for finishing flat surfaces or outside and inside cylindrical surfaces. In this research, the main focus is on flat lapping the surfaces of valve discs or nozzle seats.
- Part Size/Diameter (inch)
  - Part size is critical for equipment selection and setup in lapping operation. In this research, parts are in circle shape, thus, their sizes may be represented by their diameters.

➢ Surface Roughness of the part ($R_a$ or $R_q$ in $\mu$inch)

- Surface roughness consists of fine irregularities in the surface texture, usually including those resulting from the inherent action of the production process. Surface roughness of both before and after lapping operation is under consideration in this research. Surface roughness can be measured by a variety of instruments, including using profilometer for an estimated measurement. Surface roughness is usually presented in terms of the arithmetic average ($R_a$) or the root mean square (rms) value ($R_q$). Lapping can obtain surface roughness average from 16 to 1 $\mu$inch. The following Figure 15 shows the definition of surface roughness average ($R_a$), which is generally used.

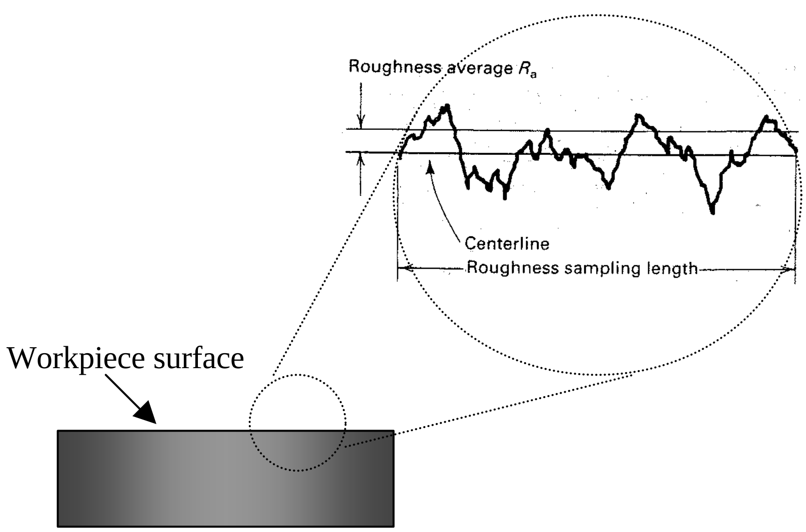
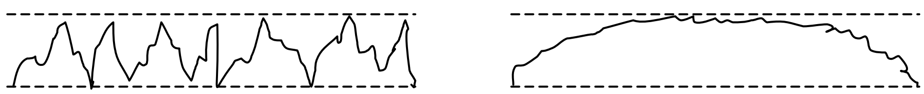



Figure 15 Surface Roughness Measured by Roughness Average ($R_a$)

- Surface Flatness of the part (light bands)

    - Normally, surface flatness is described in terms of the separation of two parallel lines or planes between which all deviations are contained. An example clarifying the difference between surface flatness and roughness is shown in the following Figure 16.



(a) (b)

Figure 16 (a) rough but flat (b) smooth but curved

Surface flatness may be measured in “light bands” unit, which can be transformed into the unit of millionths of an inch. Light bands formed by using an optical flat and a monochromatic light source represent an inexpensive yet accurate method of checking surface flatness. The monochromatic light on which the diagrammatic interpretations are based comes from a helium filled tube source that eliminates all colors except a “yellowish” orange. One wavelength of light from this source measures 23.2 millionths of an inch. However, since only one half of the wave is used in the measurement procedure, thus, the unit of measure is one half of 23.2 or 11.6 millionths of an inch. An example of band pattern on a surface, seen under an optical flat, is shown in the following Figure 17. It is these dark bands that are used in measuring the flatness of the surface.

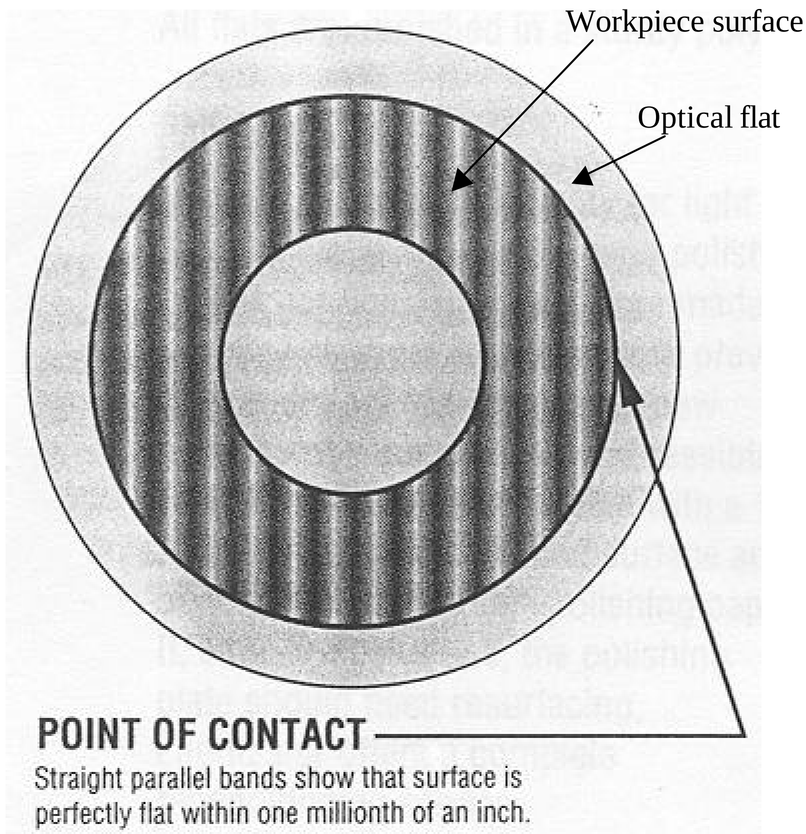



Figure 17 An Example of Light Band Patterns on a Perfectly Flat Surface(87)

- Material Removal Rate (MRR) – measured in $in^3$/minute
    - The amount of material that is removed per period of lapping time is also critical. Material removal rate may be measured by finding the difference in the height ($\Delta h$) of the workpiece before and after lapping. Then, use the $\Delta h$ to calculate volume ($in^3$), amount of

removed material. Lastly, the removed material volume can be divided by lapping time (minute) to obtain MRR.

### 4.2.2 Mechanical Lapping

Most critical parameters for mechanical lapping are the same as those in manual lapping except for the followings:

1. Pressure
   - After installing the lapping tool on a drill press or milling machine, lapping pressure can be controlled by using the handle attached to the drill press or milling machine. The weight of the lap ring/block does not play a big role here, since it will be attached to the shaft, which is installed to the drill press or milling machine. If required, the pressure can be measured using a separate special tool.
2. Speed of rotation (rpm)
   - After installing the lapping tool on a drill press or milling machine, speed of rotation is controlled by the drill press or milling machine on which the mechanical lapping tool is installed. This is generally the rotation speed of lap rings/blocks or valve discs, which is usually attached to the shaft and upper part of the drill press or milling machine. A lapping operation only requires a very slow speed of rotation, which may be measured in the unit of revolution per minute (rpm).

# 5.0 DESIGN AND IMPLEMENTATION OF EXPERIMENTS

## 5.1 Design of Experiment

The lapping operation involves many interwoven parameters that dictate the outcome of the process. Some of the critical process parameters were selected for detailed study in this research as explained in the previous section. As an avenue for better understanding the nature of each parameter and its effect on others, a series of experiments were conducted. In order to draw meaningful conclusions from the experiments, the statistical approach to experimental design is necessary. The following Table 4 summarizes parameters of interest in terms of controllable and response parameters in the experiments.

Table 4 Controllable and Response Parameters in the Experiments

| | |
|---|---|
| **Controllable Parameters** | Abrasive Grit Size, Type of Abrasive, Type of Workpiece, Workpiece Material, Lapping Technique, Initial Roughness, Pressure, Speed of Rotation, Size of Lap Ring/Block (e.g. Diameter, Weight) |
| **Response Parameters** | Surface Finish (Roughness), Flatness, Amount of Removed Material, Lapping Time |

Factorial designs have been found to be most efficient for experiments that involve the study of the effects of two or more factors, which is the case here. Thus, in this research, the experiments were designed using factorial design concepts. Here, in each complete trial or replication of the experiment all possible combinations of the levels of the factors are investigated.[83] Two-level both full and fractional factorial designs ($2^k$ factorial designs*) were used in this research. The main reason for using fractional factorial along with full factorial was that as the number of factors in a $2^k$ factorial design increases, the number of runs required for a complete replicate of the design rapidly outgrows the available resources.

In this section, the process of experimental design and developed preliminary test protocols are explained.

### 5.1.1 Preliminary Test Protocol For Manual Lapping

#### 5.1.1.1 Objectives of the Experiment

The following are three main objectives of conducting a set of experiments for manual lapping:

- Explore the fundamental relationships among key parameters of manual lapping in a scientific approach.
- Gather data on the most critical parameters for a given set of product constraints.

---

* $2^k$ factorial design means the design of $k$ factors, each at only *two* levels.

- Use analysis of the results as a source of supporting information for understanding lapping parameters and their relationships and developing a protocol for the advisory system.

5.1.1.2 Parameters Under Consideration

The following sub-sections explain the parameters under consideration in conducting manual lapping experiments by classifying them into uncontrollable, controllable, and response parameters.

Uncontrollable Parameters

The following parameters are uncontrollable per se and may be considered random variations in conducting the experiments. These parameters may somewhat affect the quality of manually lapped surfaces.

- *Operator's variability* or *subjectivity*

  Uncertainties of human performance are unavoidable. This is the main reason why the outcome of manual lapping is generally inconsistent. Examples of operator's variability include pressure, rotation speed, and skill level.

- *Environmental factors*

  A manual lapping operation is preferably to be performed in a clean and steady environment. However, this is not always possible. Examples of environment factors include temperature, vibration, and dirt.

- *Application factors*

  Different lapping techniques and settings may affect the quality of lapped surfaces. Examples of application factors are whether lapping on bench or floor, how the parts and equipments are manually held, and how the tools are set at the workstation.

Controllable Parameters (Input Parameters)

The controllable parameters used in the experiments are basically process control parameters. These parameters can be categorized into “constants” and “variables”. Since the $2^k$ factorial design is used, there are only two levels for each variable.

1. Constants

- Pressure

  The weight of the lap ring is considered a source of lapping pressure here. For manual lapping, pressure is usually generated from the weight of the lap ring and compressive force from the hand. In performing this experiment, pressure is assumed to be constant due to the following limitations:

    1. Lap rings used in the experiments are available only in one size.
    2. Hand force is difficult to measure and control. In addition, manual lapping requires only light to zero hand force.

- Abrasive material

  The valve discs and nozzle seats used in this experiment are made of stainless steel. In addition, Stainless is the most widely used material for valve discs and nozzle seats. Thus, Aluminum oxide is used in the experiments since it is best suited for lapping stainless material. Aluminum oxide is a fused crystalline abrasive. Its hardness on MOHS scale is 9. Aluminum oxide has a very hard crystal structure that is slowly dulled and hard to fracture.

- Lap ring material

  For lap ring selection, an accepted practice is to choose a lap ring material that is softer than the workpiece. Cast iron is the most widely used material for lap ring. It is also softer than stainless steel material (lapping parts) that is used in the experiments.

- Part material

  Most valve discs and seats used in the experiments are made of stainless steel.

- Lap ring diameter or area

  Since there is only one size of lap ring available for the experiments, the lap ring size is a constant here. In addition, this also helps to maintain the uniformity of the lapping pressure.

Note: The different abrasive and part materials are not included in the experiments due to the limitation of their availability. However, if necessary, the same set of protocols can be used for different combinations of abrasive and part material.

2. Variables

- Abrasive grit size (in grit numbers)

  Aluminum oxide is available in grit size # 220, 320, 500, 900, and 1200. Grit size # 220 contains the coarsest abrasive grains and # 1200 contains the finest abrasive grains. The coarse grains are used for rough lapping while the fined grains are used for final finish lapping. However, using any combination of grit sizes, lapping process is usually started with the coarse grains and finished with the fine grains.

- Initial roughness of the surface to be lapped ($R_a$ μinch)

  Two different sets of surfaces are used in the experiments. The surfaces may already go through the process of rough lap with 12 μinch surface roughness or machining with 32 μinch surface roughness.

- Initial flatness of the surface to be lapped (light bands)

  Surface flatness is believed to be among critical process parameters. However, it is impossible to measure surface flatness with optical flat before lapping since the workpiece must have a reflective surface. Thus, initial flatness will not be considered in the experiments.

- Seat Width of the part (in.)

  Seat width is used in lieu of part size. It is the surface that is actually lapped upon. The following Figure 18 shows how seat width of a valve disc is measured.

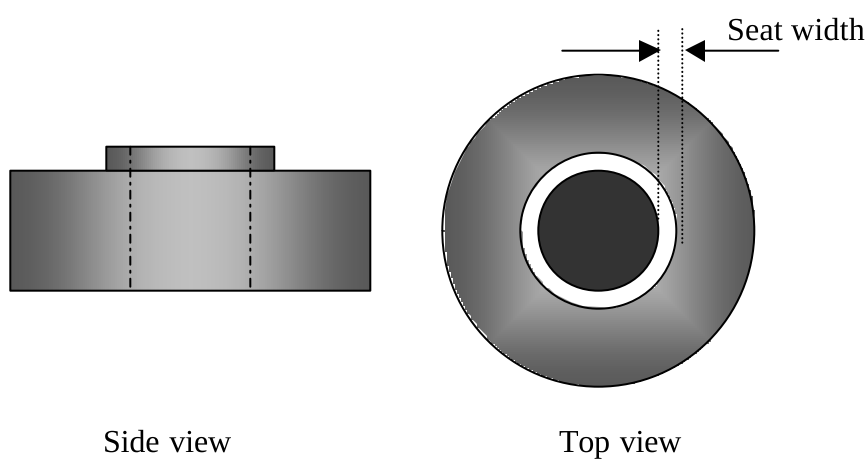



Figure 18 Seat Width of a Valve Disc

- Part type

  In the experiments, two part types (either disc or nozzle) are used.

<u>Responses (Output Parameters)</u>

- Surface Flatness (measured in Helium light-bands unit)

  After lapping is done, surface flatness is measured using an optical flat in units of Helium light-bands.

- Surface Roughness (measured in μ-inch)

  After lapping is done, surface roughness is compared and estimated using profilometer, in units of μ-inches.

- Material Removal Rate or MRR (measured in $1000^{th}$ of an inch/minute)

  To calculate MRR, two measurements are required:

  1. Amount of material removed (measured in $1000^{th}$ of an inch)

     The seat height of parts are measured both before and after the lapping process. Then, the different seat heights can be calculated. The following Figure 19 shows how seat height is measured.

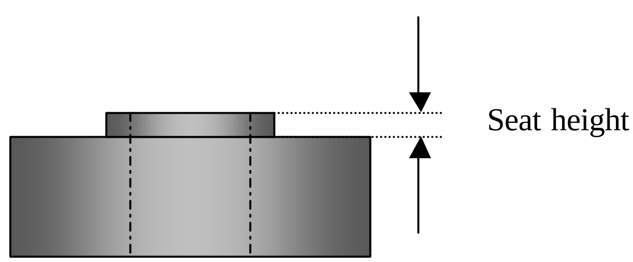



Figure 19 Measurement Methodology for Seat Height of a Valve Disc or Nozzle Seat

The difference of seat heights represents the amount of material removed by a lapping operation. Since the amount of material removed by lapping operation is very small and to avoid round off error, the difference of seat heights (inches) is timed by 1000 to come up with the unit of $1000^{th}$ of an inch.

2. Time (measured in minutes)

   Lapping time from start to finish is recorded in minutes.

Using the above two measures, then, material removal rate (1000th of an inch/minute) can be calculated by dividing amount of material removed with lapping time.

5.1.1.3 Explanation for Experimental Design

The experiment for manual lapping was designed using a full factorial design with two levels for each input variable ($2^k$ factorial design). Since there are five factors, each at two levels, the design is $2^5$ factorial design which requires 32 runs to complete all the possible combinations. It is important to note here that "abrasive grit size," which is available in five different numbers (#220, 320, 500, 900, and 1200), is broken down into three different factors (abrasive grit size for rough, finish, and lap). Abrasive grit sizes for rough and finish have two levels, while abrasive grit size for lap has only one level and becomes a constant. The following Table 5 summarizes factors and their levels used in the manual lapping experiment. Table 47 and Table 48 in Appendix B show all possible combination of factors and levels at design and final stages respectively. Due to limitations of time and resources, the experiment was designed and run as unreplicated factorial (32 runs without replication).

Table 5 Factors and Levels of Interests (Manual Lapping)

| **FACTORS** | **LEVELS** |
|---|---|
| Part type | Disc or Nozzle |
| Initial roughness | 12 μ-inch or 32 μ-inch |
| Part size (seat width) | $D_1$ inch or $D_2$ inch |
| Abrasive grit size for rough lap* | #220 or #320 |
| Abrasive grit size for finish lap* | #500 or #900 |

5.1.2 Preliminary Test Protocol for Mechanical Lapping (PLAT--Prototype Lapping Tool)

The experiments on mechanical lapping were carried out using the prototype lapping tool as explained in section 4.1 and Appendix A.

5.1.2.1 <u>Objectives of the experiment</u>

The four main objectives of conducting a set of experiments for mechanical lapping were to:

- Evaluate the efficiency of the mechanical lapping in comparison to manual lapping method and standardize the lapping process for the PLAT.

*Abrasive grit size #1200 is used for final lap to all parts, thus considered a constant.

- Explore the fundamental relationships among key parameters of mechanical lapping using a scientific approach.
- Gather data on the most critical parameters for a given set of product constraints.
- Use analysis of the results as a source of supporting information for understanding lapping parameters and their relationships and developing a protocol for the advisory system.

5.1.2.2 Factors Under Consideration

The following sub-sections explain the factors under consideration in conducting mechanical lapping experiments by classifying them into uncontrollable, controllable, and response parameters.

Uncontrollable Parameters

The following parameters are uncontrollable per se and may be considered random errors in conducting the experiments. These parameters may, somewhat, affect the quality of lapped surfaces.

- *Environmental factors*

  Lapping operation is preferably to be performed in a clean and steady environment. However, that is not always a possibility. The lapping tool is to be set on a drill press or a milling machine, which, at times, is dirty and generates atypical vibration while the machine is running. Examples of environment factors include temperature, vibration, and dirt (scrap).

- *Application factor*

    The mechanical lapping tool used in the experiments is a prototype. There is no established rule or standard procedure on how to use the tool. Thus, there may be some random errors from how the tool is set and operated.

- *Mechanical factors*

    Since the experiments are dealing with machine tools (mechanical lapping tool, milling machine, and drill press), conditions of the various mechanical components may be sources of random errors. Examples of mechanical factors include wear & tear of the parts.

Controllable Parameters (Input Parameters)

As in manual lapping, the controllable parameters used in the experiments are basically process control parameters. However, there are more parameters involved in mechanical lapping than in manual lapping. These parameters can be categorized into "constants" and "variables". Since the $2^k$ factorial design is used, there are only two levels for each variable.

1. Constants

- Abrasive material

  Aluminum oxide is used in the experiments with the same reasons as stated in the experiment protocol of manual lapping.

- Lap ring material

  Cast iron is used as lap ring material in the experiments with the same reasons as stated in the experiment protocol of manual lapping.

- Part material

  All valve discs and nozzle seats used in the experiments are made of stainless steel.

- Pressure

  For lapping operation using mechanical lapping, the lapping tool is installed on a drill press or a milling machine. Thus, pressure is usually generated by pressing down the upper part to the base part. However, in conducting the experiments, pressure is assumed to be constant due to the following limitations:

  1. Pressure from milling machine is generally difficult to control and measure.
  2. Lapping requires only a light hand force. Too much pressure will drive the upper and lower part of the tool together with the same speed of rotation, which is undesirable. Thus, the upper part of the tool is usually brought down just to touch the lower part with a minimal pressure from the drill press or milling machine.

- Lap ring diameter or area

  Only one size of lap ring is used here due to the limitation of the lapping tool (the lap ring holder is designed to hold only a certain size of lap ring).

<u>Note</u>: As in the experiments of manual lapping, the different abrasive and part materials are not under consideration here. In developing the module of abrasive selection, the appropriate combinations of abrasive and part materials are based mainly on experts'

suggestion and lapping literature. However, if necessary, the same set of protocols can be used for different combination of abrasive and part material.

2. Variables

Most of the variables in the manual lapping experiments are also under consideration here. These variables include abrasive grit size, initial roughness of the part surface to be lapped, initial flatness of the part surface to be lapped, seat width of the part, part type. However, there is an additional variable under consideration for mechanical lapping experiments. The additional variable is speed of rotation, which can be controlled by the drill press/milling machine on which the mechanical lapping tool is installed. Two levels of rotation speed are used in the experiments.

Responses (Output Parameters)

As in manual lapping experiments, there are four responses for mechanical lapping:

- Surface Flatness (measured in Helium light-bands unit)
- Surface Roughness (measured in μ-inch)
- Material Removal Rate or MRR (measured in $1000^{th}$ of an inch/minute), which is calculated by deviding amount of material removed by lapping time.

5.1.2.3 Explanation for Experimental Design

The experiments for mechanical lapping were designed using fractional factorial with two levels for each input variable. As explained in section 5.1.2.2, there are 6 controllable factors to be investigated. If a full factorial design were to be used, a complete replicate of the $2^6$ design (64 runs) would be required. In this full factorial design, only 6 of the 63 degrees of freedom correspond to main effects, and only 15 degrees of freedom correspond to two-factor interactions. The remaining 42 degrees of freedom are associated with three-factor and higher interactions. However, it can be reasonably assumed here that high-order interactions are negligible, thus, information on the main effects and low-order interactions may be obtained by running only a fraction of the complete factorial experiment.

For mechanical lapping experiment, a one-half fraction of $2^6$ with resolution *VI* ($2_{VI}^{6-1}$ design) was used with design generators $F = \pm ABCDE$. In this design, only 32 runs are required instead of 64 runs. This $2_{VI}^{6-1}$ design is the highest resolution possible for this fractional design. The higher the resolution, the less restrictive the assumptions that are required regarding which interactions are negligible in order to obtain a unique interpretation of the data. In this case, each main effect is aliased with a single 5-factor interaction and each 2-factor interaction is aliased with a single 4-factor interaction. The following Table 6 summarizes factors and levels used in mechanical lapping experiment.

Table 6 Factors and Levels of Interest (Mechanical Lapping)

| FACTORS | LEVELS |
|---|---|
| Part type | Disc or Nozzle |
| Speed of Rotation | 70 rpm or 80 rpm |
| Initial roughness | 12 $\mu$-inch or 32 $\mu$-inch |
| Part size (seat width) | $D_1$ inch or $D_2$ inch |
| Abrasive grit size for rough lap* | #220 or #320 |
| Abrasive grit size for finish lap* | #500 or #900 |

Table 54 and Table 52 in Appendix B show the process of constructing the one-half fractions including all possible combination of factors and levels at design and final stages respectively.

## 5.2 Implementation of Experiments

Both manual and mechanical lapping experiments were conducted at two lapping facilities as mentioned in section 3.4. The following sub-sections explain in detail how the experiments were conducted, including precautions and limitations.

*Abrasive grit size #1200 is used for final lap to all parts, thus considered a constant.

### 5.2.1 Manual Lapping

Valve discs and nozzle seats were prepared based on the experiment protocol. Then, they were manually and individually lapped by two skilled lapping operators. All the work was done on working tables with lapping operators standing next to them at both lapping facilities. Details on working conditions and ergonomics of the operation will be discussed later in section 6.2.1. The process was carefully timed and recorded. Finally, surface flatness, roughness, lapping time, and amount of removed material were measured. The following guidelines on how to lap valve discs and nozzle seats (prepared by United State Products Co.) were used.

#### 5.2.1.1 Lapping Valve Discs

1. Ensure that the work area is clean. Have several lint-free wipes opened and ready for use.
2. Ensure that the appropriate sized laps for the disc diameter are available.
3. Select the type of compound to use for the first lapping sequence.
4. Set the lap on a lint-free wipe to avoid dirt contamination.
5. Apply a small amount of compound onto only the lap surface that will come in contact with the disc surface. Wipe any excess compound of the lap.
6. Begin lapping by placing the disc flat onto the lap (avoid dropping it or placing it on the lap at an angle), then without any downward pressure apply a circular oscillating motion for three seconds followed by a one-eighth turn. Alternate between these two turns for approximately two minutes.

7. Remove the disc from the lap by pulling it straight up. If done properly suction or popping effect should occur. Avoid removing it horizontally or turning it off.
8. Clean the disc surface and the entire lap (top, bottom, sides) using an approved cleaner/degreaser (fast drying, leaving a dry surface with no residue and not harm the environment). Let each part evaporate dry. Do not wipe dry.
9. Using a 7x-measuring magnifier and a flashlight, inspect the disc surface and determine whether the next lapping phase is to be done with the same compound. A dull, dark, gray satin finish or "matte" and no obvious surface imperfections on the disc indicate that a finer compound can be used.
   - If the same compound is to be used in the next lapping sequence**,** repeat steps 5 though 9 one or two more times.
   - If a finer compound is to be used in the next lapping sequence, clean the lap with a cleaner/degreaser and store it in a moisture-proof container to keep it from rusting. Dedicate the lap to 'C' (coarse), "M" (medium), or "P" (polish) surface by marking its storage container. This will prevent cross-contamination of coarser grit compounds onto the laps dedicated for polishing (finer grit compounds).
10. Select the finer compound (500 grit or 900 grit) to be used in the next lapping sequence
11. Lap with the finer compound by repeating steps 4 through 9 using the lap dedicated to the compound type used. Use the same circular oscillating and turning motion technique as described in step 6 for approximately two minutes. During these short intervals, clean only the disc surface using a cleaner/degreaser. If inspection dictates

that lapping is required again using the same compound, repeat the procedure outlined in step 6 without reapplying any new compound. In general, using finer compounds requires shorter lapping periods but more frequent checking for surface imperfections.

12. When all surface imperfections have been removed, clean the disc surface and entire lap using a cleaner/ degreaser as in step 8 and allow each part to evaporate dry. Do not wipe dry. Return the lap to a moisture-proof container and dedicate it with an "M," to be kept strictly for use with medium lapping compound.
13. Lap with a polishing compound (1200 grit) by repeating steps 4 through 8 using the lap dedicated to this compound. Use the same circular oscillating and turning motion performed in step 6.
14. Inspect the disc surface using the 7x-measuring magnifier and a flashlight. Its finish should now be smooth and mirror-like, and may reveal surface imperfections not seen before.
    - If surface imperfections are discovered, repeat the lapping procedures using one of the compounds (and dedicated laps) used previously up through the polishing phase of step 13.
    - If there are no surface imperfections, repeat step 13.
15. Inspect the disc surface again using the 7x-measuring magnifier and flashlight. This final inspection is to ensure that no scratches are detected on the disc surface.

16. After the lapping procedure has been completed for this valve disc, return the disc to the valve and wrap the latter in a protective cloth then, return the lap to its moisture-proof bag or container; dedicate it with a ‘P’.

Before lapping again with the laps, make plans to recondition each of them. The lap must be flat in order to impart flatness to the parts.

5.2.1.2 Lapping Nozzle Seats

Follow the procedure for lapping valve discs with the following exceptions:

**Step 5**: Squeeze a small amount of the compound on various spots of the lap.

**Step 6**: With the side of the 1ap containing the compound facing you, hold the lap such that al1 five of your fingers point towards you and extend approximately 1 inch beyond the surface edge of the lap.

Then, invert the 1ap and place it flat onto the nozzle seat, avoiding any downward pressure, and proceed with a similar circular oscillating and turning action as described in step 6. Move the lap with one hand to execute the circular oscillating motion and move the valve containing the nozzle seat with the other hand to execute the turning motion. If the nozzle is secured in a vice, execute the turning action by moving your body around the nozzle.

**Step 9**: The intermediate lapping sequence (s) using the finer compounds can be eliminated. Therefore, if inspection at step 9 indicates that no further lapping is required with the "C" compound, skip steps 10 through 12 and continue with the lapping procedure using the "P" compound in step 13.

**Step 15**: As part of the final inspection, measure the nozzle seat width with the 7x measuring magnifier according to the valve manufacturer's instructions, if any.

5.2.1.3 Lapping Issues and Precautions

The precautions must be observed when lapping either a valve disc or nozzle seat:

- Never lap using downward pressure, figure-eight motions, linear motions, or rocking motions.
- Never lap using a circular oscillating motion without an accompanying turning motion. Doing so could produce "phonograph" type scratches (i.e. spiraling from the inside to the outside of the part's surface or vice versa).
- Never remove a lap from a part either horizontally or by “turning” at an ang1e.
    - Never apply more compound to a lap beyond that required to cover the area to be lapped. Doing so could cause rounded corners on the part after lapping.
    - Never allow the compound to remain on its container after application. Doing so could contaminate the remaining compound in the container.
    - Never wipe a surface dry after lapping. Doing so could cause cross-scratching of the part surface, especially when coarse compounds are used. Cleaner/degreaser can be sprayed onto a lint-free wipe and the part may be lightly touched around its circumference.

### 5.2.2 Mechanical Lapping

All the guidelines and precautions for manual lapping were also applied while conducting mechanical lapping experiments. The differences were in that, for mechanical lapping, there was no need for holding parts (valve discs and nozzle seats) and lap rings. The mechanical lapping tool was installed on a milling machine at each lapping facility. The upper part (shaft) of the tool was attached to the driver of the milling machine, while the base part was clamped to the lower table of the milling machine. Before starting the machine, the upper part, which was holding parts to be lapped, was brought down just to touch the lap ring, which was securely placed in the ring plate. Then, all the lapping routines were done as in manual lapping.

# 6.0 RESULTS OF LAPPING EXPERIMENTS

## 6.1 Statistical Analyses Employed

The experiments for both manual and mechanical lapping were designed using the statistical approach as explained in section 5.1. The main reason for doing so was to draw meaningful conclusions from the data. However, to confirm some significant effects and better explain some response data, various statistical analysis techniques were explored and the results were compared and consolidated. This section discusses the different statistical techniques employed in the data analysis.

### 6.1.1 Analysis of Variance

Analysis of variance (ANOVA) models are versatile statistical tools for studying the relation between a response variable and one or more explanatory (controllable) variables. These models do not require any assumptions about the nature of the statistical relation between the response and explanatory variables, nor do they require that the explanatory variables be quantitative.

#### 6.1.1.1 Manual Lapping

As previously mentioned, the experiment for manual lapping was designed using a full factorial with two levels for each input variable ($2^k$ factorial design). Since there are five factors, each at two levels, the design is $2^5$ factorial design which requires 32 runs to complete all the possible combination. The data obtained from a single replicate of the $2^5$ experiment are shown in Table 49 (Appendix B).

6.1.1.2 Mechanical Lapping

As previously mentioned, one-half fractions of $2^6$ design of resolution 6 ($2_{VI}^{6-1}$) were used in the design of mechanical lapping experiments. The data obtained from the experiments are shown in Table 53 (Appendix B). Generally, for data analysis of fractional factorial design, a preliminary ANOVA analysis is first run using the obtained data. Then the controllable parameter(s) that has minimal or no effect on all responses can be dropped from consideration to obtain a full $2^5$ factorial design with single replication or a full $2^4$ factorial design with 2 replications and so on. However, it is not necessary to do so, if it is reasonable to assume that high-order interactions are negligible, which is the case here.

### 6.1.2 Non-parametric Test (the Kruskal-Wallis Test)

In situations where the normality assumption is unjustified, the experimenter may wish to use an alternative procedure to the F test analysis of variance that does not depend on this assumption. Such a procedure has been developed by Kruskal and Wallis. This test is used to test the null hypothesis that the *a* treatments are identical against the alternative hypothesis that some of the treatments generate observations that are larger than others. The Kruskal-Wallis test is a nonparametric alternative to the usual analysis of variance[(83)].

### 6.1.3 Regression Analysis

The regression analysis was done along with ANOVA to compare the results. The regression function describes the nature of the statistical relationship between the mean response and the level(s) of the predictor variable(s). However, some quantitative and indicator variables were used in this research, and if some quantitative variables are used with regression models, the regression results may not be theoretically identical to those obtained with analysis of variance models. Thus, the results from regression analysis, discussed in this section, are intended to be compared with those obtained from ANOVA and to give additional information on relationships among parameters.

#### 6.1.3.1 Manual Lapping

For regression analysis in this research, regression models with bilinear interaction terms were used. The following equation is a general form of a full regression model for manual lapping.

$$E\{Y\} = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_1X_2 + b_7X_1X_3 + b_8X_1X_4 + b_9X_1X_5 + b_{10}X_2X_3 + b_{11}X_2X_4 + b_{12}X_2X_5 + b_{13}X_3X_4 + b_{14}X_3X_5 + b_{15}X_4X_5$$

where:

$b_{0\text{-}15}$ = Regression coefficients

$X_1$ = Part Type, $X_2$ = Initial Roughness, $X_3$ = Part Diameter (Seat Width), $X_4$ = Grit Rough, $X_5$ = Grit Finish

6.1.3.2 Mechanical Lapping

As in manual lapping, regression models with bilinear interaction terms were used. The following equation is a general form of a full regression model for mechanical lapping.

$$E\{Y\} = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_6 + b_7X_1X_2 + b_8X_1X_3 + b_9X_1X_4 + b_{10}X_1X_5 + b_{11}X_1X_6 + b_{12}X_2X_3 + b_{13}X_2X_4 + b_{14}X_2X_5 + b_{15}X_2X_6 + b_{16}X_3X_4 + b_{17}X_3X_5 + b_{18}X_3X_6 + b_{19}X_4X_5 + b_{20}X_4X_6 + b_{21}X_5X_6$$

where:

$b_{0\text{-}21}$ = Regression coefficients

$X_1$ = Part Type, $X_2$ = Speed of Rotation (rpm), $X_3$ = Initial Roughness,

$X_4$ = Part Diameter (Seat Width), $X_5$ = Grit Rough, $X_6$ = Grit Finish

6.1.4 Multivariate Analysis

Multivariate linear regression was used because the data under consideration included simultaneous measurements on some variables and also helped explain the relationships among parameters.

6.1.4.1 Manual Lapping

The correlation matrix in Table 7 indicates that there is a significant correlation between *Surface Flatness* and *Surface Roughness*. Thus, these two responses are under consideration here. The following equation shows a general form on the multivariate linear regression model.

$$Y_{(n \times m)} = \begin{bmatrix} Y_{11}Y_{12} \\ Y_{21}Y_{22} \\ . \\ . \\ . \\ Y_{321}Y_{322} \end{bmatrix}, \; Y_{n1} = \textit{Surface Flatness},\; Y_{n2} = \textit{Surface Roughness}$$

$$Z_{(n \times (r+1))} = \begin{bmatrix} Z_{11}Z_{12}...Z_{115} \\ Z_{21}Z_{22}...Z_{215} \\ . \\ . \\ . \\ Z_{321}Z_{322}...Z_{3215} \end{bmatrix}, \; b_{((r+1)xm)} = \begin{bmatrix} b_{01}b_{02} \\ b_{11}b_{12} \\ . \\ . \\ . \\ b_{151}b_{152} \end{bmatrix}, \; \varepsilon_{(n \times m)} = \begin{bmatrix} e_{11}e_{12} \\ e_{21}e_{22} \\ . \\ . \\ . \\ e_{321}e_{322} \end{bmatrix}$$

or $\mathbf{Y}_{(n \times m)} = \mathbf{Z}\; b_{((r+1)x m)} + e_{(n \times m)}$

6.1.4.2 Mechanical Lapping

The correlation matrix in Table 21 indicates that there is a significant correlation between *MRR* and *Surface Roughness*. Thus, these two responses are under consideration here. The following equation shows a general form on the multivariate linear regression model.

$$Y_{(n \times m)} = \begin{bmatrix} Y_{11}Y_{12} \\ Y_{21}Y_{22} \\ . \\ . \\ . \\ Y_{321}Y_{322} \end{bmatrix}, \; Y_{n1} = \textit{MRR},\; Y_{n2} = \textit{Surface Roughness}$$

$$Z_{(n\ x\ (r+1))} = \begin{bmatrix} Z_{11}Z_{12}...Z_{121} \\ Z_{21}Z_{22}...Z_{221} \\ . \\ . \\ . \\ Z_{321}Z_{322}...Z_{3221} \end{bmatrix}, \ b_{((r+1)xm)} = \begin{bmatrix} b_{01}b_{02} \\ b_{11}b_{12} \\ . \\ . \\ . \\ b_{211}b_{212} \end{bmatrix}, \ \varepsilon_{(n\ x\ m)} = \begin{bmatrix} e_{11}e_{12} \\ e_{21}e_{22} \\ . \\ . \\ . \\ e_{321}e_{322} \end{bmatrix}$$

or $\mathbf{Y}_{(n\ x\ m)} = \mathbf{Z}\ b_{((r+1\ )x\ m)} + e_{(n\ x\ m)}$

The results from each statistical analysis are shown and discussed in the following sub-sections in the forms of ANOVA tables, graphs, and explanation of the results ordered by each response variable

## 6.2 Manual Lapping Results

The data obtained from a single replicate of the $2^5$ experiment are shown in Table 49 (Appendix B). This section shows and explains results of data analysis for *Surface Flatness, Surface Roughness,* and *Material Removal Rate* as response variables. Each response was tested using statistical techniques explained in the previous section with a set of controllable parameters one at a time. The controllable parameters are *Part Type, Part Diameter (Seat Width), Initial Roughness, Grit Rough,* and *Grit Finish*. In addition, since manual lapping is highly related to human performance, this section begins with a discussion of ergonomics and human factor issues involved in the experiment.

### 6.2.1 Ergonomics and Human Factors Analyses

The performance of manual lapping in the experiments was inevitably subjective due to lapping operator's skills, even though a guideline (as explained in section 5.2.1) was followed in conducting experiments in this research. The ergonomics and human factor analysis were done in order to provide more information and to better understand some process variations. In this section, results of some analysis on ergonomics and human factor aspects with respect to manual lapping are summarized and explained. Tasks and work-station analysis were done using ErgoMaster$^{TM}$ software.

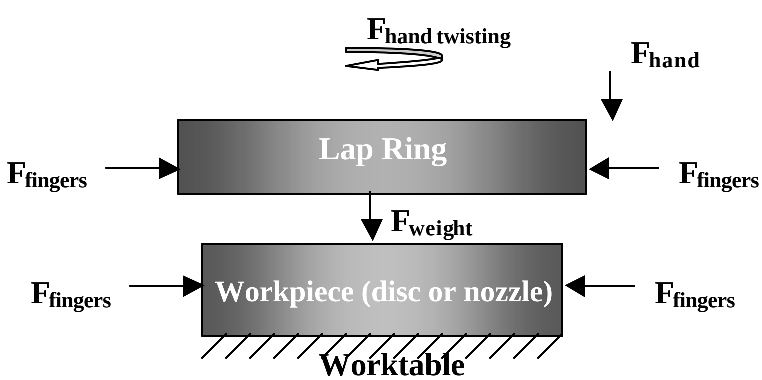



Figure 20 Possible Forces Involved in Manual Lapping

The above Figure 20 shows a simplified diagram of possible forces occurred in manual lapping. The lap ring is generally held and twisted by hand while performing the manual lapping operation, thus there are horizontal compressive forces and rotating force created by fingers and hand. A vertical hand force is inevitable in manual lapping, even though, the lapping operator should apply minimal or no vertical pressure while manually lapping parts. Considering the previously mentioned forces, it is difficult to maintain balance among those forces while performing manual lapping operation, thus, process variations are inevitable. Some examples of process variation are: horizontally sliding off from desired position of lap rings, flipping (vertical movement) of lap rings or parts, and too much vertical hand force.

Manual lapping requires significant efforts from body motion. Figure 56 in Appendix B shows critical body parts involved in performing the operation. Figure 56 also shows the degree of severity of each critical body part. From a process point of view, basically, the operator used his right hand to hold a lap ring, while standing, and used his left hand to hold parts (one at a time). The operator then constantly twists his right wrist until the job was done. Thus, the right hand and wrist were the most critical body parts in performing manual lapping. Since, manual lapping was done while the operator was standing, some fatigues in legs, back, and neck are inevitable.

The results from a task assessment (from ErgoMaster™ ) are summarized here:

1. A manual lapping operation does not reduce or eliminate bending and/or twisting of the trunk and, thus, can lead to the generation of excessive torque, compression, shear forces and torsion on the spine, especially in the lumbar region which can ultimately lead to soft tissue and/or joint failure (i.e., muscle strain, neuropathy, herniated disc, etc.).
2. Since the lapping operator is usually in a standing position, this task does not reduce or eliminate squatting and kneeling and can create an excessive amount of force to be placed on the knee joints. Kneeling

directly on the knee joint can result in inflammation, cartilage damage and/or pain. Squatting creates excessive torque on the knee joint, which may lead to muscle, ligament and/or joint damage.

3. A manual lapping operation requires elbows above mid torso. This posture can create excessive forces at the shoulder joint and its smaller rotator cuff complex, causing inflammation (tendonitis, bursitis) and possible failure (ruptured tendons). Tasks performed with elbows above mid-torso can also create a longer lever arm, concerning the low back, which can lead to excessive forces on the spine resulting in soft tissue and or bone injury.
4. Using extended arms while lapping may create excessive torques on the shoulder, elbow and wrist joints. If not corrected, this posture may lead to strains/sprains of soft tissue and/or joint inflammation.
5. The right wrist is extensively used in manual lapping. This deviation can cause compression of the carpal tunnel region, which houses tendons, nerves and arteries. It may ultimately lead to inflammation, poor circulation and/or neuropathy (i.e., carpal tunnel syndrome).
6. The lapping operator uses static muscle loading and forceful pinch grips to hold and to lap parts. This posture can lead to muscle fatigue and poor circulation to and from the muscles ultimately leading in tissue damage and its failure. Pinch grips create excessive forces to be placed on the smaller joints of the hand and wrist, which can lead to

their failure and damage. Objects should be able to be grasped with a minimum amount of force and without slippage.

7. Manual lapping cannot be performed with either hand. This capability is important because it allows for proper rest and it minimizes excessive repetition and pacing. These are essential in minimizing injury to the wrist/hand. Muscles require sufficient time to recover from work related stresses.
8. Since the discs and lap ring generally have a round shape and smooth side surface. A forceful grip is required to perform this task. This transfers excessive forces to the smaller joints of the hand leading to injury. A poor grasp with increased gripping force may promote slippage, which inherently contribute to soft tissue/bone damage. Materials involved with this task are not easy to grasp. Ease of grip will help reduce the forces necessary to perform the tasks, which promotes a decrease in injuries to the smaller joints and the muscles of the wrist/hand.
9. Fixtures and vises are not used during manual lapping. Grasping forces must be kept low to prevent soft tissue and bony damage. When utilized, fixtures and vices contribute to diminishing the force necessary to hold an object in place. They also help to promote a safer work environment.

10. Lapping operators are exposed to repetitive motions via job rotation. Repetitive motions can lead to muscle fatigue, poor circulation and increased force necessary to perform a task. The results can be damage to muscles, tendons, ligaments, nerves and/or joints. Self-pacing allows muscles to recover following repetitive motion. Time must be allotted to permit muscle reoxygenation and the removal of accumulated waste products. When sufficient, rest pauses and breaks allow muscles to recover from repetitive tasks. Time must be allotted to permit muscle reoxygenation and the removal of accumulated waste products.

Results from work-station assessment (from ErgoMaster™) are summarized here:

1. The lapping table requires that the operator's elbows be above mid-torso. Working with elbows above mid-torso can create excessive torque along the shoulder, elbow and wrist joints, which can lead to soft tissue and/or bone damage.
2. Awkward postures are not being reduced by providing adjustable work surfaces and supports. Adjustable work surfaces and supports allow for customization of the workstation for multiple employees and/or tasks. Customizing will allow for improved support and positioning of the spine and extremities, which can decrease the stresses placed on soft tissue and bone structures.

3. To perform manual lapping on the lapping table, awkward postures are inevitable. Awkward postures place unnatural and excessive forces on the spine and extremities, which can lead to physical damage concerning soft tissue and bone structures.
4. An armrest was not provided for precision work. Precision work without an armrest can create excessive forces at the wrists and shoulders as a result of prolonged static postures, which can lead to muscle fatigue, poor circulation and neuropathy.
5. A footrest was not provided for those who needed it. Lack of a properly positioned foot support can place harmful stresses on the spine leading to physical damage to its anatomy.
6. Cushioned floor mats and footrests were not provided for employees who are required to stand for long periods. Floor mats and footrests allow for the reduction of harmful/excessive forces that are created from static positioning.

From the human factor point of view, the process of manual lapping may be improved in terms of maximizing process consistency and minimizing injuries by redesigning the task and the workstation. Some suggestions that may help improving the operation are discussed here in the following paragraphs.

Instead of manually holding a part while lapping, a fixture should be considered for clamping the part. In doing so, the part will be better stabilized and minimize the process variation. As previously mentioned, parts may move or flip if they are held by hands, which will deteriorate the surface quality. Thus, using fixtures will help minimize (or eliminate) such process variation. The fixtures should be fixed with the lapping table and adjustable to fit a variety of part types and sizes. Using fixtures will also minimize the hand and finger injuries from grasping the parts.

Since the discs and lap ring generally have a round shape and smooth side surface, a forceful grip is required to perform the operation. Using a fixture (with an easier-to-grasp side surface) to hold a part or lap ring should also be considered, instead of directly holding it. In doing so, the hand and finger injuries of grasping the parts will be minimized. In addition, the hand movement will be more under controlled, thus, improving process consistency. The fixtures should also be adjustable to fit a variety of part types and sizes.

The workstation should also be redesigned such that bending is not required for lapping operators to perform the operation. The height of work table should be adjustable and at the operator’s chest level to minimize the bending and, thus, the back injury. In addition, a chair should also be provided to minimize body fatigue, which indirectly affects the operator’s performance.

### 6.2.2 Correlations Among Responses (Manual Lapping) and Multivariate ANOVA

Table 7 shows the correlation matrix of *Surface Flatness, Surface Roughness, and MRR.*

Table 7 Correlation Matrix for Responses (Manual Lapping)

| | ***Surface Flatness*** | ***Surface Roughness*** | ***MRR*** |
|---|---|---|---|
| ***Surface Flatness*** | 1 | -0.554 | -0.2831 |
| ***Surface Roughness*** | | 1 | -0.0746 |
| ***MRR*** | | | 1 |

As can be seen in the Table 7, *Surface Flatness* and *Surface Roughness* are the only pair that contains reasonably high correlation (55.4%). The p-values from regressing each pair of the three responses also confirm that correlation between *Surface Flatness* and *Surface Roughness* exists.

Several multivariate ANOVA (MANOVA) statistics were computed, i.e. Wilks' lambda, Pillai trace, and Hotelling-Lawley trace. These statistics are used to determine whether a particular effect has a significant relationship with the group of dependent variables being modeled (*Surface Flatness* and *Roughness*). Table 8 shows significant effects at 99% confidence level when considering *Surface Flatness* and *Roughness* together as one response matrix.

Table 8 Significant Effects with respect to *Surface Flatness* and *Roughness* Matrix (Manual Lapping)

| **Variable** | **P-value from Wilks' Lambda Statistic** |
|---|---|
| *Part Type* | $6.47 \times 10^{-14}$ |
| *Part Diameter* | $7.77 \times 10^{-16}$ |
| *Initial Roughness* | 0 |
| *Part Type*Part Diameter* | $7.23 \times 10^{-7}$ |
| *Part Type*Initial Roughness* | $3.24 \times 10^{-13}$ |
| *Part Diameter*Initial Roughness* | $9.99 \times 10^{-16}$ |

The significant effect shown in Table 8 agrees with the results from ANOVA of *Surface Flatness* and *Roughness* separately. The meaning of these effects will be explored further at the process level in the next sub-section.

### 6.2.3 Surface Flatness

This section shows the results from statistical analyses with respect to *Surface Flatness*. The explanation of findings after consolidating results from different statistical analyses can be found at the end of this section. (See Table 12 for a brief summary of significant effects found from different statistical analyses.)

Table 9 Analysis of Variance Table for *Surface Flatness* (Manual Lapping)

| Source | Sum of Squares | Df | Mean Square | F-Ratio | P-Value |
|---|---|---|---|---|---|
| MAIN EFFECTS | | | | | |
| A:Part_Type | 0.125 | 1 | 0.125 | 0.33 | 0.5756 |
| B:Part_Diameter | 10.125 | 1 | 10.125 | 26.45 | 0.0001 |
| C:Initial_Roughness | 0.125 | 1 | 0.125 | 0.33 | 0.5756 |
| D:Grit_Rough | 0.0 | 1 | 0.0 | 0.00 | 1.0000 |
| E:Grit_Finish | 0.0 | 1 | 0.0 | 0.00 | 1.0000 |
| INTERACTIONS | | | | | |
| AB | 0.125 | 1 | 0.125 | 0.33 | 0.5756 |
| AC | 6.125 | 1 | 6.125 | 16.00 | 0.0010 |
| AD | 0.0 | 1 | 0.0 | 0.00 | 1.0000 |
| AE | 0.0 | 1 | 0.0 | 0.00 | 1.0000 |
| BC | 0.125 | 1 | 0.125 | 0.33 | 0.5756 |
| BD | 0.0 | 1 | 0.0 | 0.00 | 1.0000 |
| BE | 0.0 | 1 | 0.0 | 0.00 | 1.0000 |
| CD | 0.0 | 1 | 0.0 | 0.00 | 1.0000 |
| CE | 0.0 | 1 | 0.0 | 0.00 | 1.0000 |
| DE | 0.0 | 1 | 0.0 | 0.00 | 1.0000 |
| RESIDUAL | 6.125 | 16 | 0.382813 | | |
| TOTAL (CORRECTED) | 22.875 | 31 | | | |

The above ANOVA table indicates that *Part Diameter* and interaction between *Part Type* and *Initial Roughness* have significant effects on *Surface Flatness* at a 99% significance level.

Residuals vs. predicted *Surface Flatness* plot indicates that the data violate the normality assumption. However, since the measurement was an approximation and it was reasonable to assume that the data, in fact, came from a normally distributed population (when a precise measurement applied), the data were not transformed and Kruskal-Wallis test was run to compare the results with those from ANOVA. The nonparametric Kruskal-Wallis test is a statistical tool that is appropriate for data with an unknown or unspecified distribution, which is likely the case for *Surface Flatness* data.

The results from Kruskal-Wallis confirm that different levels of *Part Diameter* do affect *Surface Flatness*. Table 10 summarizes the p-values from Kruskal-Wallis test of *Surface Flatness* vs. other parameters.

Table 10 P-values from Kruskal-Wallis Test for *Surface Flatness* vs. Other Parameters

| **Test Parameters** | **P-value** |
|---|---|
| Flatness vs. Part Type | 0.292702 |
| *Flatness vs. Part Diameter* | *0.000026* |
| Flatness vs. Initial Roughness | 0.292702 |
| Flatness vs. Grit Rough | 1.0 |
| Flatness vs. Grit Finish | 1.0 |

Figure 21 shows mean plots of *Surface Flatness* vs. different levels of other controllable parameters.

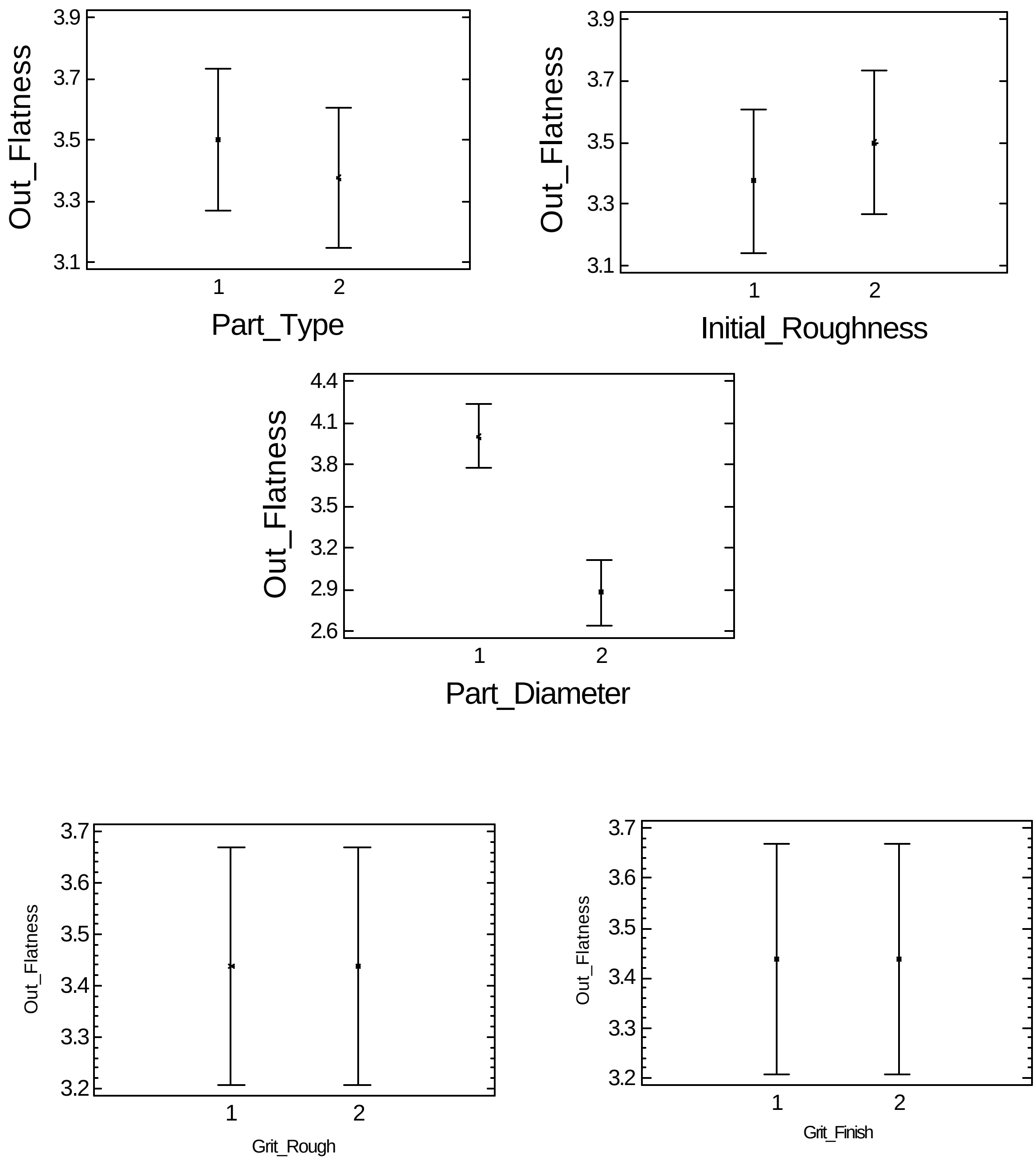



Figure 21 Mean Plots of *Surface Flatness* vs. Other Controllable Parameters

Mean plots indicate the following remarks:

- For different levels of *Part Diameter*, the mean plot clearly indicates that the higher the *Part Diameter*, the lower the obtained *Surface Flatness*.
- For different levels of *Part Type*, the mean plot indicates that the higher the *Part Type*, the slightly lower the obtained *Surface Flatness*.
- For different levels of *Initial Roughness*, the mean plot indicates that the higher the *Initial Roughness*, the higher the obtained *Surface Flatness*.

The results in Table 9 also indicate that there is an interaction effect between *Part Type* and *Initial Roughness*. Figure 22 shows an interaction plot between the two parameters with respect to *Surface Flatness.*

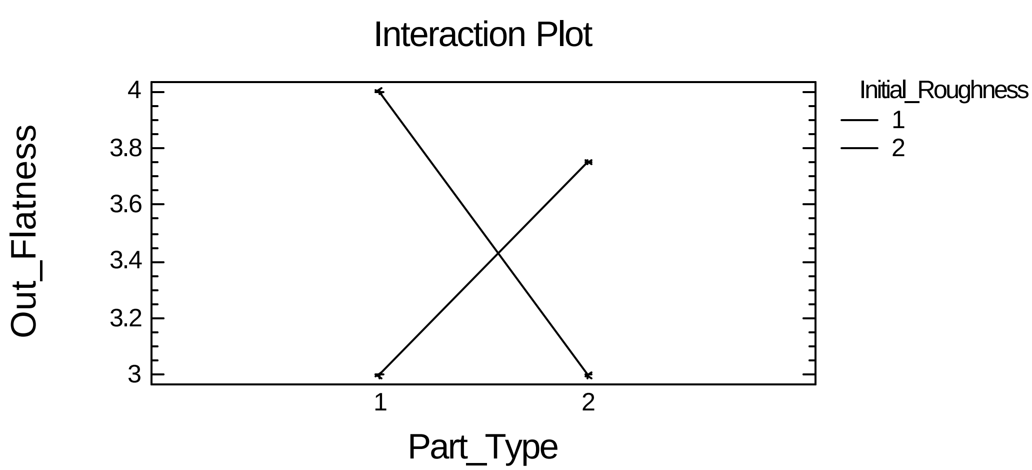



Figure 22 Interaction Plot between *Part Type* and *Initial Roughness* with respect to *Surface Flatness*

Table 11 ANOVA Results of Fitting a Multiple Regression Model to Describe the Relationship Between *Surface Flatness* and Significant Independent Variables (Manual Lapping)

| Source | Sum of Squares | Df | Mean Square | F-Ratio | P-Value |
|---|---|---|---|---|---|
| Model | 16.5 | 4 | 4.125 | 17.47 | 0.0000 |
| Residual | 6.375 | 27 | 0.236111 | | |
| Total (Corr.) | 22.875 | 31 | | | |

R-squared = 72.1311 percent
R-squared (adjusted for d.f.) = 68.0024 percent

The equation below is the best model with respect to its highest adjusted $R^2$ comparing with other possible models.

```
Out_Flatness = 1.1875 + 2.5*Part_Type - 1.125*Part_Diameter
               + 2.75*Initial_Roughness
               - 1.75*Part_Type*Initial_Roughness
```

Since the P-value of the above model in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level. The R-squared statistic indicates that the model as fitted explains 72.13% of the variability in *Surface Flatness*. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is also relatively high (68%). In sum, *Part Type, Part Diameter, Initial Roughness,* and interactions of *Part Type*Initial Roughness* have statistically significant effects on *Surface Flatness*. However, *Part Diameter* seems to be the most important parameter with respect to *Surface Flatness* by all model selection techniques.

Table 12 A Summary of Significant Effects with respect to Different Statistical Analyses (Manual Lapping – Surface Flatness)

| **Significant Effects** | **Test** | **Significance Level (a )** | **Statistics*** |
|---|---|---|---|
| Part Diameter | ANOVA<br>Kruskal-Wallis<br>Regression | 0.01<br>0.01<br>0.01 | 0.0001<br>0.00003<br>0.0001 |
| Part Type*Initial Roughness | ANOVA<br>Regression | 0.01<br>0.01 | 0.0010<br>0.0010 |
| Part Type,<br>Part Diameter,<br>Initial Roughness,<br>Part Type*Initial Roughness | Regression Model | 0.01 | 0.000(model)<br>Adjusted-$R^2$ =<br>68.0% |

*Statistics are p-value, unless otherwise indicated.

The *Surface Flatness,* obtained from manual lapping, is generally related to *Part Type* (discs or nozzle seats), *Part Diameter*, and *Seat Width.* The ability to obtain better surface flatness tends to decrease when lapping seats with wider diameters and widths. For different part types, it is more difficult to obtain the desired flatness when lapping nozzle seats rather than lapping valve discs because manually stabilizing nozzles on the worktable while lapping is more difficult than stabilizing discs. Nozzles usually are tall and have small bases, thus, more difficult to maintain their stability without a well-designed fixture.

The results from data analysis of manual lapping experiments indicate that *Part Diameter (Seat Width)* and interaction of *Part Type* and *Initial Roughness* have statistically significant effects on *Surface Flatness*. The results, however, indicate that lapping parts with wider seat widths (larger diameters) results in better surface flatness, which does not follow the rule of thumb mentioned in the previous paragraph. The reason could be due to human ability to maintain wrist posture on small objects (discs) and from random variations in the experiments, e.g. the initial surface flatness (before lapping) of seats with wider seat widths is significantly better than that of seats with narrower widths. The significant interaction effect can be explained separately for discs and nozzles. From the experiments, discs with lower (better) initial roughness tend to have better surface flatness after manual lapping, while discs with higher (worse) initial roughness tend to have higher (worse) flatness after lapping.

On the other hand, nozzles with lower (better) initial roughness tend to have worse surface flatness after manual lapping, while nozzles with higher (worse) initial roughness tend to have lower (better) flatness after lapping. *Part Type* effects are equally high for both levels of *Initial Roughness*, but in the different directions. Again, the reason could be from different in the *Initial Surface Flatness* of parts. In this research, surface flatness cannot be measured before lapping because measuring surface flatness by optical flats requires that the surface have a mirror finish, which unfortunately was not the case for experiments done in this research. However, the effects of *Part Type* and *Initial Roughness* can be intuitively explained. In general, discs are easier to lap, thus, desired flatness is easier to obtain. Parts with a higher initial roughness (rougher surface) require more lapping time, thus increase the risk of deterioration of surface flatness, especially for manual lapping. The results from data analysis also indicate that surface flatness and surface roughness are negatively correlated.

### 6.2.4 Surface Roughness

This section shows the results from statistical analyses with respect to *Surface Roughness*. The explanation of findings after consolidating results from different statistical analyses can be found at the end of this section. (See Table 16 for a brief summary of significant effects found from different statistical analyses.)

Table 13 Analysis of Variance Table for *Surface Roughness*

| Source | Sum of Squares | Df | Mean Square | F-Ratio | P-Value |
|---|---|---|---|---|---|
| MAIN EFFECTS | | | | | |
| A:Part_Type | 13.1328 | 1 | 13.1328 | 7.95 | 0.0123 |
| B:Part_Diameter | 7.50781 | 1 | 7.50781 | 4.55 | 0.0489 |
| C:Initial_Roughness | 32.0 | 1 | 32.0 | 19.37 | 0.0004 |
| D:Grit_Rough | 0.0078125 | 1 | 0.0078125 | 0.00 | 0.9460 |
| E:Grit_Finish | 0.03125 | 1 | 0.03125 | 0.02 | 0.8923 |
| INTERACTIONS | | | | | |
| AB | 0.03125 | 1 | 0.03125 | 0.02 | 0.8923 |
| AC | 6.57031 | 1 | 6.57031 | 3.98 | 0.0634 |
| AD | 0.0 | 1 | 0.0 | 0.00 | 1.0000 |
| AE | 0.0078125 | 1 | 0.0078125 | 0.00 | 0.9460 |
| BC | 9.57031 | 1 | 9.57031 | 5.79 | 0.0285 |
| BD | 0.03125 | 1 | 0.03125 | 0.02 | 0.8923 |
| BE | 0.0078125 | 1 | 0.0078125 | 0.00 | 0.9460 |
| CD | 0.0078125 | 1 | 0.0078125 | 0.00 | 0.9460 |
| CE | 0.03125 | 1 | 0.03125 | 0.02 | 0.8923 |
| DE | 0.0078125 | 1 | 0.0078125 | 0.00 | 0.9460 |
| RESIDUAL | 26.4297 | 16 | 1.65186 | | |
| TOTAL (CORRECTED) | 95.375 | 31 | | | |

The ANOVA table indicates that *Part Type* and *Initial Roughness* have statistically significant effects on *Surface Roughness* at 95% significance level, while *Part Diameter* may have some slight effect on *Surface Roughness,* i.e. *Part Diameter* will become statistically significant at a higher level of significance. In addition, the interaction between *Part Diameter* and *Initial Roughness* also has a significant effect on *Surface Roughness* at 95% significance level.

A plot of residuals vs. predicted *Surface Roughness* indicates that the data violate normality assumption. However, since the measurement was an approximation and it is reasonable to assume that the data, in fact, came from a normally distributed population (when a precise measurement was applied), the data were not transformed, instead Kruskal-Wallis test was run to compare the results with those from ANOVA. The results of Kruskal-Wallis test indicate that *Part Type* and *Initial Surface Roughness* have effects on *Surface Roughness*. These are the only two pairs that are statistically significant. The significance of these two main effects follows the results from ANOVA analysis. However, *Part Diameter,* which seems to be statistically significant by ANOVA analysis, is not statistically (border line) significant by Kruskal-Wallis test. The following Table 14 summarizes the p-values from Kruskal-Wallis test of *Surface Roughness* vs. other parameters.

Table 14 P-values from Kruskal-Wallis Test for *Surface Roughness* vs. Other Parameters

| **Test Parameters** | **P-value** |
|---|---|
| *Roughness vs. Part Type* | *0.00820262* |
| Roughness vs. Part Diameter | 0.546793 |
| *Roughness vs. Initial Roughness* | *0.000827434* |
| Roughness vs. Grit Rough | 0.876425 |
| Roughness vs. Grit Finish | 0.741066 |

The following Figure 23 shows mean plots of *Surface Roughness* vs. different levels of other parameters.

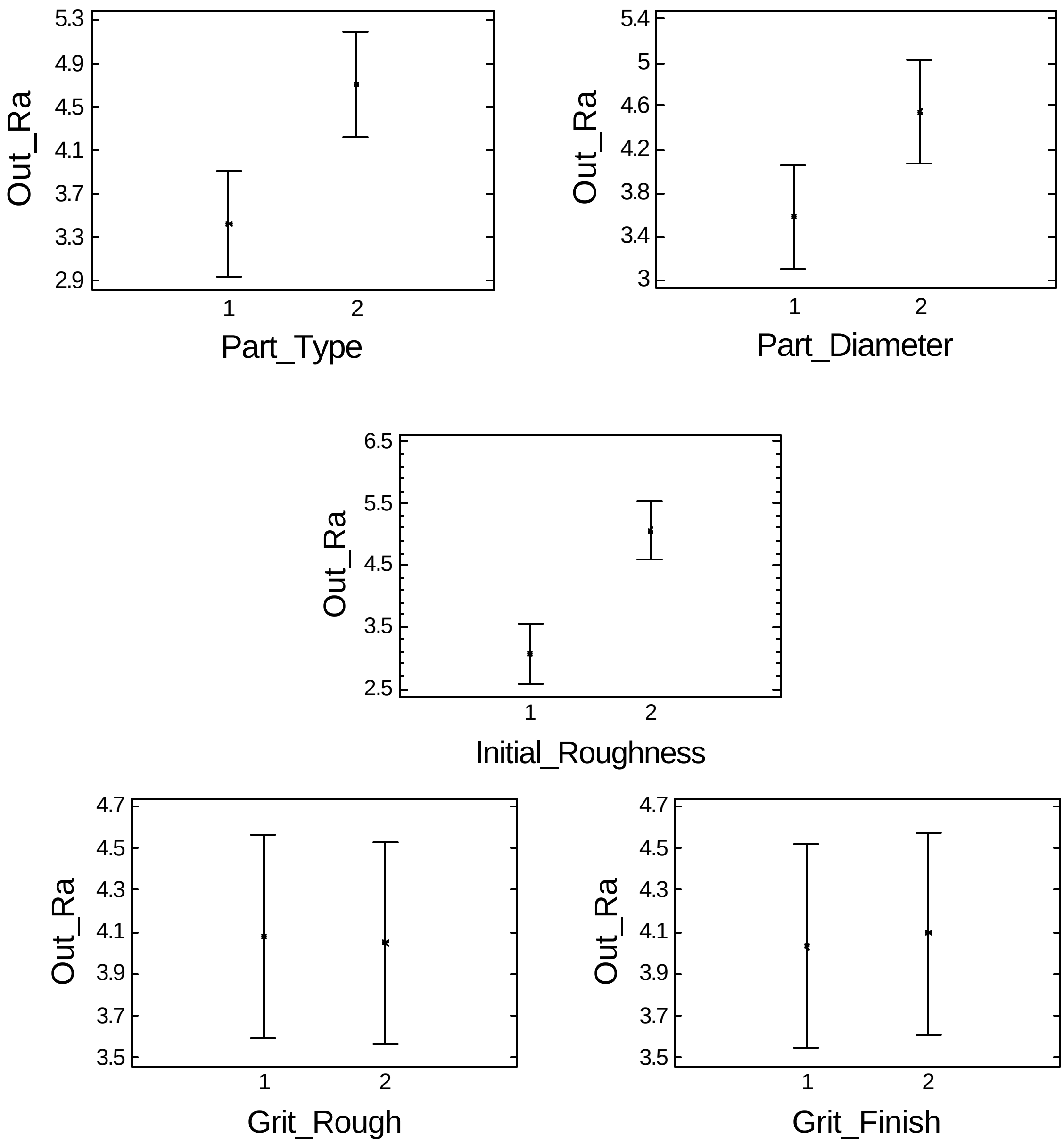



Figure 23 Mean Plots of *Surface Roughness* vs. Other Controllable Parameters

Mean plots indicate the following remarks:

- For different levels of *Part Type*, the mean plot clearly indicates that the higher the *Part Type*, the higher the obtained *Surface Roughness*.
- For different levels of *Part Diameter*, the mean plot clearly indicates that the higher the *Part Diameter*, the higher the obtained *Surface Roughness*.
- For different levels of *Initial Roughness*, the mean plot indicates that the higher the *Initial Roughness,* the slightly higher the obtained *Surface Roughness*.
- The plots indicate that there is no significant difference in means for the two levels of *Grit Rough* and *Grit Finish* with respect to *Surface Roughness*.

The results in Table 13 also indicate that there is an interaction effect between *Part Diameter* and *Initial Roughness*. The following Figure 24 shows an interaction plot between the two parameters with respect to *Surface Roughness.*

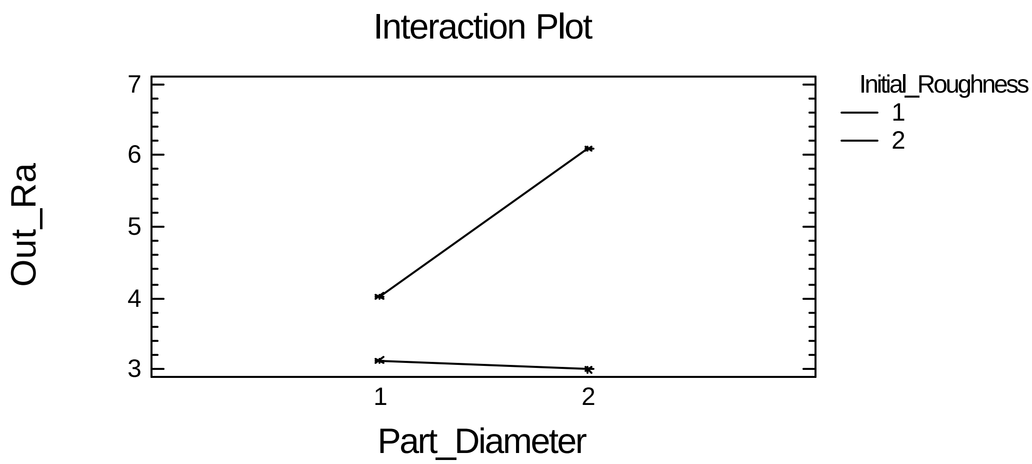



Figure 24 Interaction Plot between *Part Diameter* and *Initial Roughness* with respect to *Surface Roughness* (Out_Ra)

Table 15 ANOVA Results of Fitting a Multiple Regression Model to Describe the Relationship Between *Surface Roughness* and Significant Independent Variables (Manual Lapping)

| Source | Sum of Squares | Df | Mean Square | F-Ratio | P-Value |
|---|---|---|---|---|---|
| Model | 68.7812 | 5 | 13.7562 | 13.45 | 0.0000 |
| Residual | 26.5938 | 26 | 1.02284 | | |
| Total (Corr.) | 95.375 | 31 | | | |

R-squared = 72.1166 percent
R-squared (adjusted for d.f.) = 66.7545 percent

The equation below is the best model with respect to its highest adjusted $R^2$ comparing with other possible models.

```
Out_Ra = 6.6875 + 1.8125*Part_Type*Initial_Roughness
         + 2.1875*Part_Diameter*Initial_Roughness
         - 1.4375*Part_Type - 2.3125*Part_Diameter
         - 4.0*Initial_Roughness
```

Since the P-value of the above model in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level. The R-squared statistic indicates that the model as fitted explains 72.12% of the variability in *Surface Roughness.* The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is also relatively high (67%). In sum, *Part Type, Part Diameter, Initial Roughness*, and interactions of *Part Type*Initial Roughness* and *Part Diameter*Initial Roughness* have statistically significant effects on *Surface Roughness*.

Table 16 A Summary of Significant Effects with respect to Different Statistical Analyses (Manual Lapping- Surface Roughness)

| **Significant Effects** | **Test** | **Significance Level ($\alpha$)** | **Statistics*** |
|---|---|---|---|
| Part Type | Kruskal-Wallis | 0.01 | 0.0082 |
| Part Diameter | ANOVA<br>Regression | 0.05<br>0.05 | 0.0489<br>0.0489 |
| Initial Roughness | ANOVA<br>Kruskal-Wallis<br>Regression | 0.01<br>0.01<br>0.01 | 0.0004<br>0.00083<br>0.0004 |
| Part Diameter*Initial Roughness | ANOVA<br>Regression | 0.05<br>0.05 | 0.0285<br>0.0285 |
| Part Type,<br>Part Diameter,<br>Initial Roughness,<br>Part Diameter*Initial Roughness<br>Part Type*Initial Roughness | Regression Model | 0.01 | 0.000 (model)<br>Adjusted-$R^2$ = 66.8% |

*Statistics are p-value, unless otherwise indicated.

*Surface Roughness,* obtained from manual lapping, is generally related to *Initial Roughness* and *Grit Size*. Parts with higher initial roughness (rougher surface) tend to get higher surface roughness after lapping. The combination of grit sizes used also plays an important role here. A higher grit size can, sometimes, deteriorates the surface if not used properly. In addition, if there is a jump from a much coarser grain to a very fine grain, the surface may not be as smooth as intended.

The results from data analysis of manual lapping experiments indicate that *Part Type*, *Part Diameter (Seat Width)*, *Initial roughness*, and interaction of *Part Diameter* and *Initial Roughness* have statistically significant effects on *Surface Roughness*. The results, unsurprisingly, indicate that compared with lapping nozzle seats, lapping valve discs provides better surface roughness. This findings follow a standard rule of thumb that lapping valve discs is generally easier than lapping nozzle seats. The significant interaction effect can be explained separately for different levels of *Part Diameter (Seat Width)*. From the experiments, parts with higher initial roughness (rougher surfaces) tend to have higher (worse) surface flatness after manual lapping, which just follows the rule of thumb previously mentioned. However, *Part Diameter* effects are much higher when lapping parts with higher initial roughness. In addition, lapping wider diameter (seat width) parts with higher initial roughness results in significantly higher surface roughness (rougher surface), comparing with lapping narrower diameter (seat width) parts. Again, this finding follows a standard rule of thumb that lapping smaller surface is easier to maintain control over the process. The results from data analysis also indicate that surface roughness and surface flatness are negatively correlated.

### 6.2.5 Material Removal Rate (MRR)

This section shows the results from statistical analyses with respect to *MRR*. The explanation of findings after consolidating results from different statistical analyses can be found at the end of this section. (See Table 20 for a brief summary of significant effects found from different statistical analyses.)

Table 17 Analysis of Variance Table for *Material Removal Rate* (*MRR*)

| Source | Sum of Squares | Df | Mean Square | F-Ratio | P-Value |
|---|---|---|---|---|---|
| MAIN EFFECTS | | | | | |
| A:Part_Type | 0.000189579 | 1 | 0.000189579 | 0.02 | 0.8890 |
| B:Part_Diameter | 0.0000354314 | 1 | 0.0000354314 | 0.00 | 0.9519 |
| C:Initial_Roughness | 0.031625 | 1 | 0.031625 | 3.35 | 0.0857 |
| D:Grit_Rough | 0.00128776 | 1 | 0.00128776 | 0.14 | 0.7165 |
| E:Grit_Finish | 0.00397391 | 1 | 0.00397391 | 0.42 | 0.5254 |
| INTERACTIONS | | | | | |
| AB | 0.00323642 | 1 | 0.00323642 | 0.34 | 0.5661 |
| AC | 0.0649544 | 1 | 0.0649544 | 6.89 | 0.0184 |
| AD | 0.00116821 | 1 | 0.00116821 | 0.12 | 0.7294 |
| AE | 0.00405887 | 1 | 0.00405887 | 0.43 | 0.5210 |
| BC | 0.00198812 | 1 | 0.00198812 | 0.21 | 0.6522 |
| BD | 0.00603269 | 1 | 0.00603269 | 0.64 | 0.4354 |
| BE | 0.0402078 | 1 | 0.0402078 | 4.27 | 0.0555 |
| CD | 0.0000171347 | 1 | 0.0000171347 | 0.00 | 0.9665 |
| CE | 0.00230242 | 1 | 0.00230242 | 0.24 | 0.6279 |
| DE | 0.00138701 | 1 | 0.00138701 | 0.15 | 0.7063 |
| RESIDUAL | 0.150821 | 16 | 0.00942632 | | |
| TOTAL (CORRECTED) | 0.313286 | 31 | | | |

The above ANOVA table indicates that none of the parameters has a significant main effect on *MRR* at 95% significance level (*Initial Roughness* will become significant at a lower significance level). However, the interaction between Part Type and Initial Roughness is significant.

The following Figure 25 shows mean plots of *Material Removal Rate* vs. different levels of other controllable parameters.

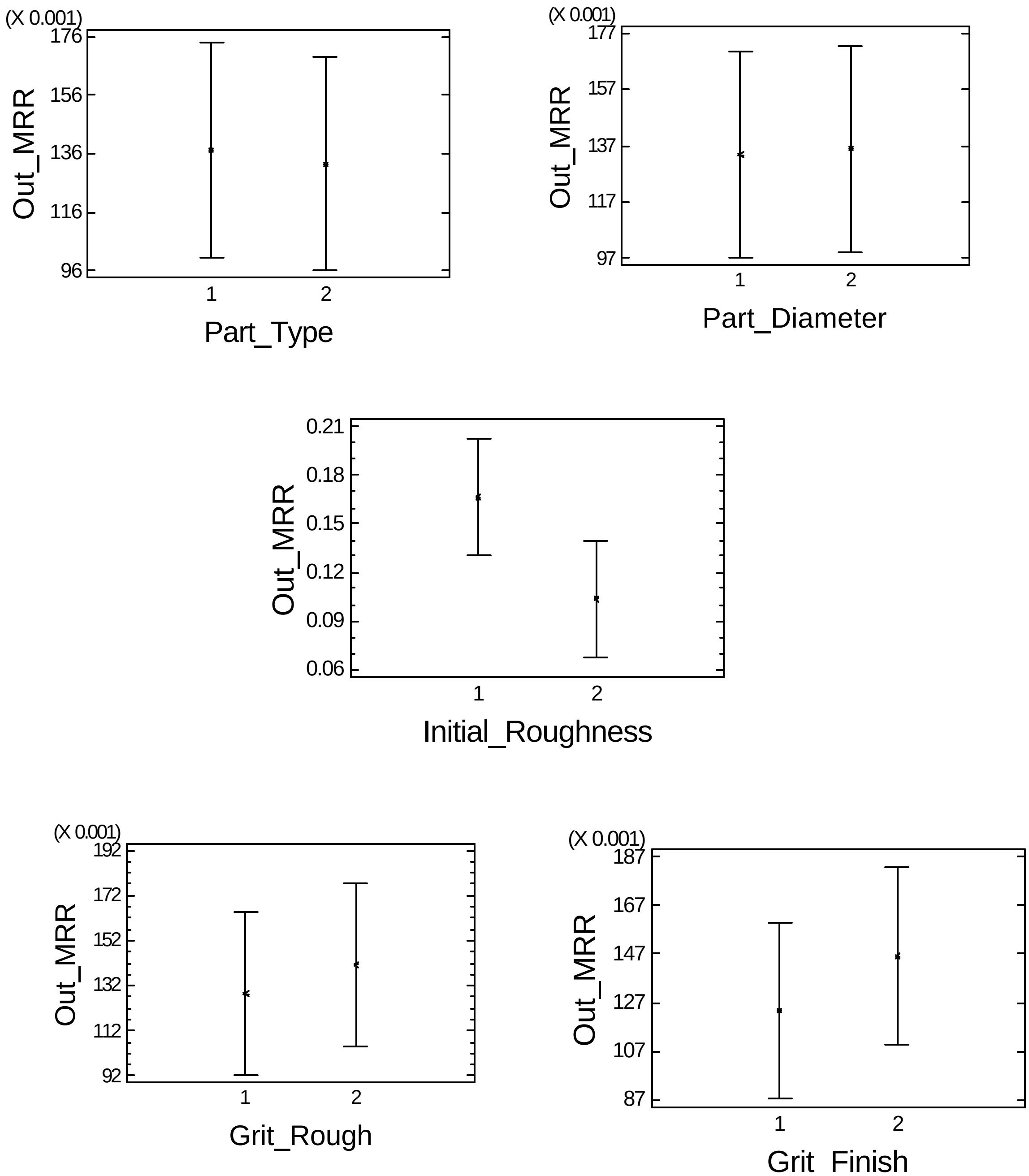



Figure 25 Mean Plots of *Material Removal Rate* vs. Other Controllable Parameters

Mean plots indicate the following remarks:

- For different levels of *Part Type* and *Part Diameter*, the mean plots indicate that there is no significant difference in *MRR*.
- For different levels of *Initial Roughness*, the mean plot clearly indicates that the higher the *Initial Roughness*, the lower the *MRR*.
- For different levels of *Grit Rough*, the mean plot indicates that the higher the *Grit Rough*, the higher the *MRR*.
- For different levels of *Grit Finish*, the mean plot indicates that the higher the *Grit Finish*, the higher the *MRR*.

The ANOVA results in Table 17 indicate that there is an interaction effect between *Part Type* and *Initial Roughness*. The following Figure 29 shows an interaction plot between the two parameters with respect to *Material Removal Rate*.

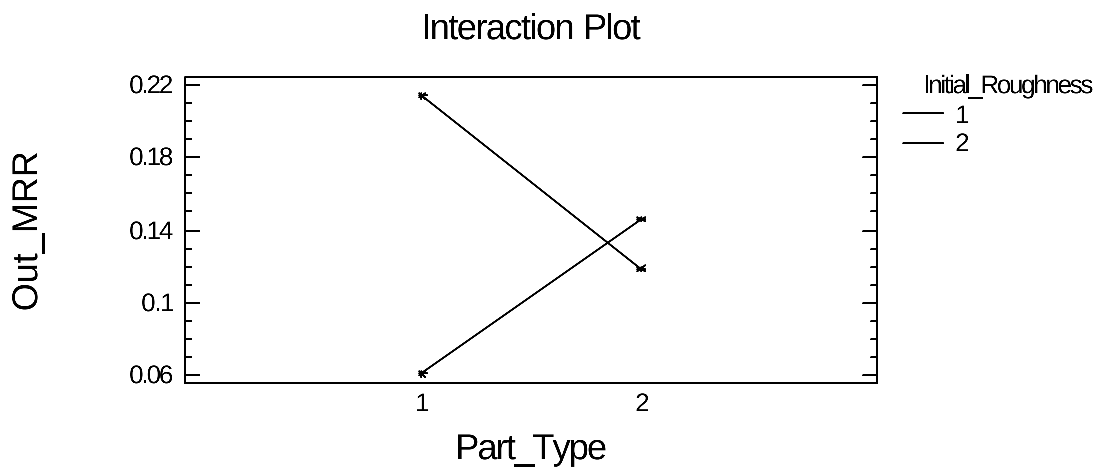



Figure 26 Interaction Plot between *Part Type* and *Initial Roughness* with respect to *Material Removal Rate* (*Out_MRR*)

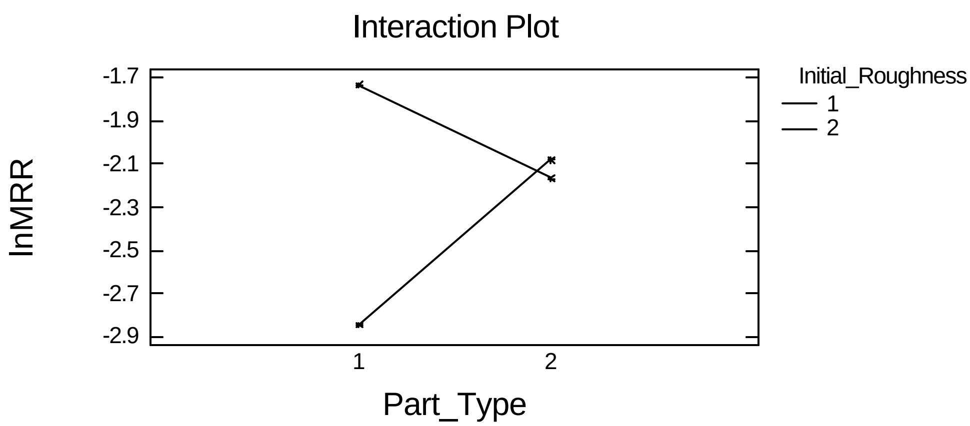
Scatter plots do not indicate any major concern regarding the inequality of the variances. However, plot of residuals versus predicted *MRR* does indicate some problem regarding the violation of normal assumption and equality of variance.

A data transformation is often used to deal with violation of normality assumption and equality of variance problems. As the response variable (*MRR*) is a rate, the log transformation seems a reasonable candidate[83]. Thus, the analysis was also done on $MRR^* = \ln(MRR)$. See Table 50 in Appendix B for data on $MRR^*$.

Table 18 Analysis of Variance Table for Transformed *Material Removal Rate* [ln(*MRR*)]

| Source | Sum of Squares | Df | Mean Square | F-Ratio | P-Value |
|---|---|---|---|---|---|
| MAIN EFFECTS | | | | | |
| A:Part_Type | 0.221827 | 1 | 0.221827 | 0.75 | 0.3983 |
| B:Part_Diameter | 0.0739222 | 1 | 0.0739222 | 0.25 | 0.6232 |
| C:Initial_Roughness | 2.12105 | 1 | 2.12105 | 7.20 | 0.0163 |
| D:Grit_Rough | 0.0396567 | 1 | 0.0396567 | 0.13 | 0.7185 |
| E:Grit_Finish | 0.0566306 | 1 | 0.0566306 | 0.19 | 0.6669 |
| INTERACTIONS | | | | | |
| AB | 0.0121999 | 1 | 0.0121999 | 0.04 | 0.8413 |
| AC | 2.87635 | 1 | 2.87635 | 9.77 | 0.0065 |
| AD | 0.0418974 | 1 | 0.0418974 | 0.14 | 0.7110 |
| AE | 0.37176 | 1 | 0.37176 | 1.26 | 0.2778 |
| BC | 0.03945 | 1 | 0.03945 | 0.13 | 0.7192 |
| BD | 0.0486574 | 1 | 0.0486574 | 0.17 | 0.6898 |
| BE | 1.47505 | 1 | 1.47505 | 5.01 | 0.0398 |
| CD | 0.0256405 | 1 | 0.0256405 | 0.09 | 0.7717 |
| CE | 0.0553759 | 1 | 0.0553759 | 0.19 | 0.6703 |
| DE | 0.000136946 | 1 | 0.000136946 | 0.00 | 0.9831 |
| RESIDUAL | 4.71187 | 16 | 0.294492 | | |
| TOTAL (CORRECTED) | 12.1715 | 31 | | | |

The ANOVA results in Table 18 indicate that *Initial Roughness* has become a main effect with respect to ln(*MRR*). The results also indicate that there are two interaction effects that are statistically significant (*Part Type* vs. *Initial Roughness* and *Part Diameter* vs. *Grit Finish*). Figure 27 shows interaction plots of the significant pairs.



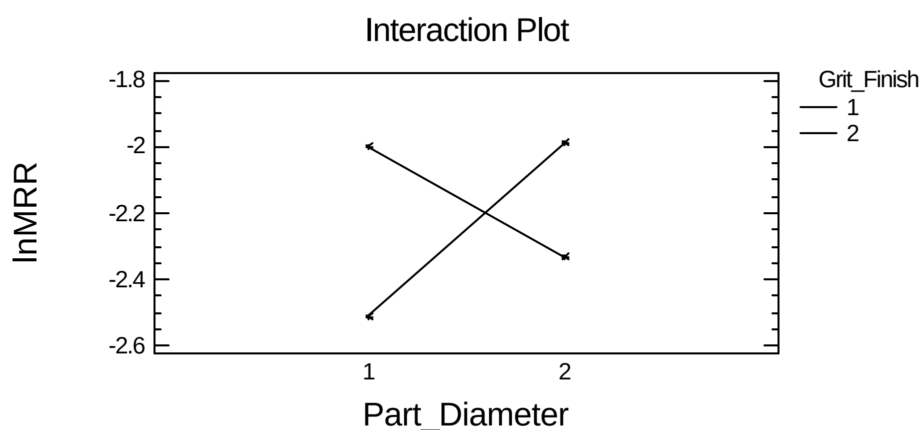




Figure 27 Interaction Plots between *Part Type* vs. *Initial Roughness* and *Part Diameter* vs. *Grit Finish* w.r.t ln(*MRR*)

Table 19 ANOVA Results of Fitting a Multiple Regression Model to Describe the Relationship Between *MRR* and Significant Independent Variables (Manual Lapping)

| Source | Sum of Squares | Df | Mean Square | F-Ratio | P-Value |
|---|---|---|---|---|---|
| Model | 0.140986 | 6 | 0.0234977 | 3.41 | 0.0135 |
| Residual | 0.1723 | 25 | 0.00689199 | | |
| Total (Corr.) | 0.313286 | 31 | | | |

R-squared = 45.0024 percent
R-squared (adjusted for d.f.) = 31.803 percent

The equation below is the best model with respect to its highest adjusted $R^2$ comparing with other possible models.

```
Out_MRR = 0.286393 - 0.275189*Part_Type + 0.214787*Part_Diameter
          - 0.333195*Initial_Roughness + 0.23497*Grit_Finish
          + 0.180214*Part_Type*Initial_Roughness
          - 0.141788*Part_Diameter*Grit_Finish
```

Since the P-value of the above model in the ANOVA table is less than 0.05, there is a statistically significant relationship between the variables at the 95% confidence level. However, the R-squared statistic indicates that the model as fitted explains 45% of the variability in *MRR*. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is also low (31%). This means that the parameters included in the model may not be the best combination to explain *MRR*. However, these parameters do have some sort of relationship with respect to *MRR*. In sum, *Part Type*, *Part Diameter*, *Initial Roughness*, *Grit Finish*, and interactions of *Part Type**Initial Roughness* and *Part Diameter**Grit Finish* more or less have statistically significant effects on *MRR*.

Table 20 A Summary of Significant Effects with respect to Different Statistical Analyses [Manual Lapping – MRR and ln(MRR)]

| **Significant Effects** | **Test** | **Significance Level (a )** | **Statistics*** |
|---|---|---|---|
| Initial Roughness | ANOVA<br>Regression | 0.05<br>0.05 | 0.0163<br>0.0163 |
| Part Type*Initial Roughness | ANOVA<br>Regression | 0.05<br>0.05 | 0.0184<br>0.0184 |
| Part Diameter*Grit Finish | ANOVA<br>Regression | 0.05<br>0.05 | 0.0398<br>0.0398 |
| Part Type, Part Diameter, Initial Roughness, Grit Finish,<br>Part Diameter*Grit Finish<br>Part Type*Initial Roughness | Regression Model | 0.05 | 0.0135 (model)<br>Adjusted-$R^2$ = 31.8% |

*Statistics are p-value, unless otherwise indicated.

*MRR*, obtained from manual lapping, is generally related to *Part Diameter (Seat Width)* and *Grit Size*. The wider the part, the higher amount of material removed during a time unit; this theoretically results in higher *MRR.* Grit size also plays an important role here. Higher grit size (coarser grain) can remove more material during a time unit.

The results from data analysis of manual lapping experiments indicate that interactions of *Part Type* vs. *Initial Roughness* and *Part Diameter* vs. *Grit Finish* have statistically significant effects on *MRR.* The results indicate that, lapping discs with higher initial roughness (rougher surface) requires lower *MRR* than lapping discs with lower initial roughness (smoother surface). This finding does not follow the general rules of thumb. One possible reason is that higher than two-order interaction may exist e.g. an interaction among *Part Type, Initial Roughness*, and *Grit Size*. On the other hand, lapping nozzle seats with higher initial roughness (rougher surfaces) requires slightly higher *MRR* than lapping discs with lower initial roughness (smoother surfaces). The effect of initial roughness on *MRR* is very low for lapping nozzle seats, compared with that of lapping discs. The results indicate that, lapping a narrower seat (smaller diameter) part with grit # 900 results in higher *MRR* than lapping a narrower seat (smaller diameter) part with grit # 500. Again, this finding does not follow the general rules of thumb. One possible reason is that interaction higher than two orders may exist, e.g. interaction among *Part Diameter, Grit Rough,* and *Grit finish*. On the other hand, lapping wider seat (larger diameter) parts with grit # 500 results in higher *MRR* than lapping wider seat (larger diameter) parts with grit # 900. The effect of grit finish size on *MRR* is significantly smaller for lapping parts with wider width (larger diameter).

## 6.3 Mechanical Lapping Results

As in data analysis for manual lapping, the results are presented here by each response variables, i.e. *Surface Flatness, Surface Roughness,* and *Material Removal Rate.* The controllable parameters are *Part Type, Part Diameter (Seat Width), RPM, Initial Roughness, Grit Rough,* and *Grit Finish*. As previously mentioned, one-half fractions of

$2^6$ design of resolution 6 ($2_{VI}^{6-1}$) were used in design of mechanical lapping experiments. The data obtained from the experiments are shown in Table 53 (Appendix B).

### 6.3.1 Correlations Among Responses (Mechanical Lapping)

Table 21 shows the correlation matrix of *Surface Flatness, Surface Roughness,* and *MRR*.

Table 21 Correlation Matrix for Responses (Mechanical Lapping)

| | ***Surface Flatness*** | ***Surface Roughness*** | ***MRR*** |
|---|---|---|---|
| ***Surface Flatness*** | 1 | 0.2778 | 0.1699 |
| ***Surface Roughness*** | | 1 | 0.5168 |
| ***MRR*** | | | 1 |

As can be seen in Table 21, *Surface Roughness* and *MRR* is the only pair that contains reasonably high correlation (51.68%). The p-values from regressing each pair of the three responses also confirm that correlation between *Surface Roughness* and *MRR* exists.

Several multivariate ANOVA (MANOVA) statistics were computed, i.e. Wilks' lambda, Pillai trace, and Hotelling-Lawley trace. These statistics are used to determine whether a particular effect has a significant relationship with the group of dependent variables being modeled, *Surface Flatness* and *Roughness* in this case. The following

Table 22 shows significant effects at 95% confidence level when *MRR* and *Roughness* are considered together as one response matrix.

Table 22 Significant Variables with respect to *MRR* and *Surface Roughness* Matrix (Mechanical Lapping)

| **Variable** | **P-value from Wilks' Lambda Statistic** |
|---|---|
| *Part Type* | 0.0043 |
| *Part Diameter* | $2.5565 \times 10^{-8}$ |
| *Part Type*Part Diameter* | $3.0748 \times 10^{-7}$ |
| *Part Type*RPM* | 0.0419 |
| *Part Type*Initial Roughness* | 0.0047 |
| *Part Diameter*RPM* | 0.0104 |
| *Part Diameter*Grit Rough* | 0.0073 |
| *RPM*Initial Roughness* | 0.0255 |
| *Initial Roughness*Grit Rough* | 0.01845 |
| *Initial Roughness*Grit Finish* | 0.0105 |
| *Grit Rough*Grit Finish* | 0.0158 |

The significant effects shown in Table 22 are a combination of the significant effects when using ANOVA test on *MRR* and *Surface Roughness* separately. The meaning of these effects at a process level will be explained in the next sub-sections.

### 6.3.2 Surface Flatness

This section shows the results from statistical analyses with respect to *Surface Flatness*. The explanation of findings after consolidating results from different statistical analyses can be found at the end of this section. (See Table 26 for a brief summary of significant effects found from different statistical analyses.)

Table 23 Analysis of Variance Table for Surface Flatness (Mechanical Lapping)

| Source | Sum of Squares | Df | Mean Square | F-Ratio | P-Value |
|---|---|---|---|---|---|
| MAIN EFFECTS | | | | | |
| A:Part Type | 0.382813 | 1 | 0.382813 | 3.18 | 0.1048 |
| B:Part_Diameter | 0.945313 | 1 | 0.945313 | 7.86 | 0.0187 |
| C:RPM | 0.0078125 | 1 | 0.0078125 | 0.06 | 0.8040 |
| D:Initial_Roughness | 0.195313 | 1 | 0.195313 | 1.62 | 0.2314 |
| E:Grit_Rough | 0.195313 | 1 | 0.195313 | 1.62 | 0.2314 |
| F:Grit_Finish | 0.195313 | 1 | 0.195313 | 1.62 | 0.2314 |
| INTERACTIONS | | | | | |
| AB | 7.50781 | 1 | 7.50781 | 62.40 | 0.0000 |
| AC | 0.195313 | 1 | 0.195313 | 1.62 | 0.2314 |
| AD | 0.945313 | 1 | 0.945313 | 7.86 | 0.0187 |
| AE | 0.382813 | 1 | 0.382813 | 3.18 | 0.1048 |
| AF | 0.0078125 | 1 | 0.0078125 | 0.06 | 0.8040 |
| BC | 0.195313 | 1 | 0.195313 | 1.62 | 0.2314 |
| BD | 2.82031 | 1 | 2.82031 | 23.44 | 0.0007 |
| BE | 0.0078125 | 1 | 0.0078125 | 0.06 | 0.8040 |
| BF | 0.0078125 | 1 | 0.0078125 | 0.06 | 0.8040 |
| CD | 0.195313 | 1 | 0.195313 | 1.62 | 0.2314 |
| CE | 0.0078125 | 1 | 0.0078125 | 0.06 | 0.8040 |
| CF | 0.0703125 | 1 | 0.0703125 | 0.58 | 0.4622 |
| DE | 0.195313 | 1 | 0.195313 | 1.62 | 0.2314 |
| DF | 0.0078125 | 1 | 0.0078125 | 0.06 | 0.8040 |
| EF | 0.195313 | 1 | 0.195313 | 1.62 | 0.2314 |
| RESIDUAL | 1.20313 | 10 | 0.120313 | | |
| TOTAL (CORRECTED) | 15.8672 | 31 | | | |

The above ANOVA table indicates that *Part Diameter (Seat Width)* and the interactions of *Part Type* vs. *Part Diameter*, *Part Diameter* vs. *Initial Roughness*, and *Part Type* vs. *Initial Roughness* have significant effects on *Surface Flatness* at 95%

significance level. However, *Part Diameter* will become statistically significant at a lower significance level. Since the $2_{VI}^{6-1}$ design was used, because of aliasing, these effects are actually *B+ACDEF*, *AB+CDEF*, *AD+BCEF*, and *BD+ACEF* (see Table 58 in Appendix B for alias relationships). However, since it seems plausible that four-factor and higher interactions are negligible, it is safe in concluding that *Part Diameter(B)*, *Part Type* vs. *Part Diameter(AB)*, *Part Diameter* vs. *Initial Roughness(AD)*, and *Part Type* vs. *Initial Roughness (BD)* are important effects.

As in manual lapping, Kruskal-Wallis test was run here to compare the results with those from ANOVA. The following Table 24 summarizes the p-values from Kruskal-Wallis test of *Surface Flatness* vs. other controllable parameters. The results indicate that different levels of all controllable parameters do not have statistically significant effect on *Surface Flatness*. However, *Part Diameter* will become significant at a little lower significance level.

Table 24 P-values from Kruskal-Wallis Test for *Surface Flatness* vs. Other Parameters (Mechanical Lapping)

| **Test Parameters** | **P-value** |
|---|---|
| Flatness vs. Part Type | 0.406302 |
| Flatness vs. Part Diameter | 0.162251 |
| Flatness vs. RPM | 0.951549 |
| Flatness vs. Initial Roughness | 0.491051 |
| Flatness vs. Grit Rough | 0.5169 |
| Flatness vs. Grit Finish | 0.478391 |

The following Figure 28 shows mean plots of Surface Flatness vs. different levels of other controllable parameters.

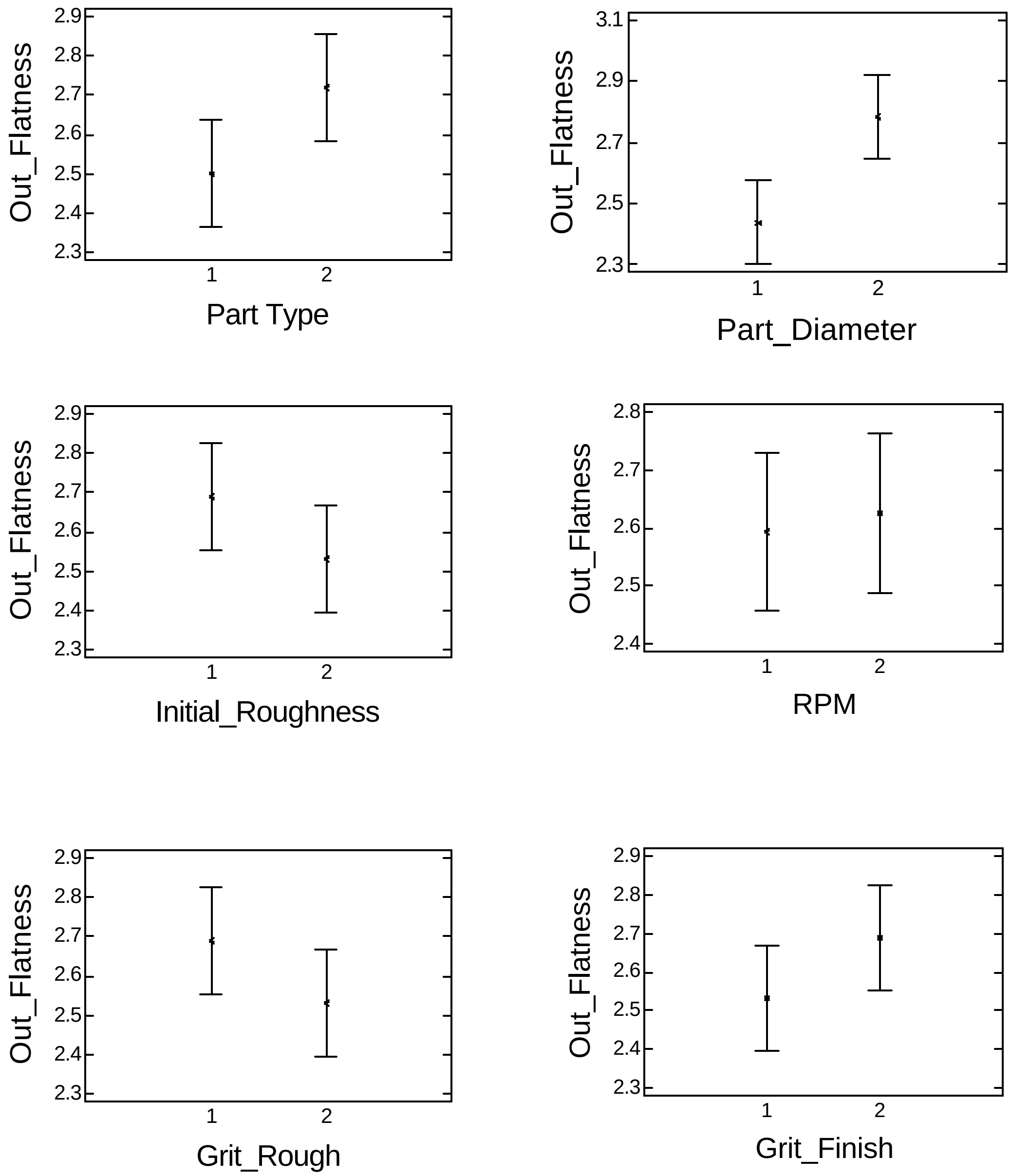



Figure 28 Mean plots of *Surface Flatness* vs. Other Controllable Parameters (Mechanical Lapping)

Mean plots in Figure 28 indicate the following remarks:

- For different levels of *Part Type*, the mean plot indicates that the higher the *Part Type*, the higher the *Surface Flatness*.
- For different levels of *Part Diameter*, the mean plot clearly indicates that the higher the *Part Diameter*, the higher the *Surface Flatness*.
- For different levels of *Initial Roughness*, the mean plot indicates that the higher the *Initial Roughness*, the lower the *Surface Flatness.*
- For different levels of *RPM*, the mean plot indicates that, for different level of *RPM* there is no different in term of *Surface Flatness*.
- For different levels of *Grit Rough*, the mean plot indicates that the higher the *Grit Rough*, the lower the *Surface Flatness.*
- For different levels of *Grit Finish*, the mean plot indicates that the higher the *Grit Finish*, the slightly higher the *Surface Flatness.*

The ANOVA results in Table 23 also indicate that three interaction effects are statistically significant with respect to *Surface Flatness*. The three interactions are *Part Type* vs. *Part Diameter*, *Part Type* vs. *Initial Roughness*, and *Part Diameter* vs. *Initial Roughness.*

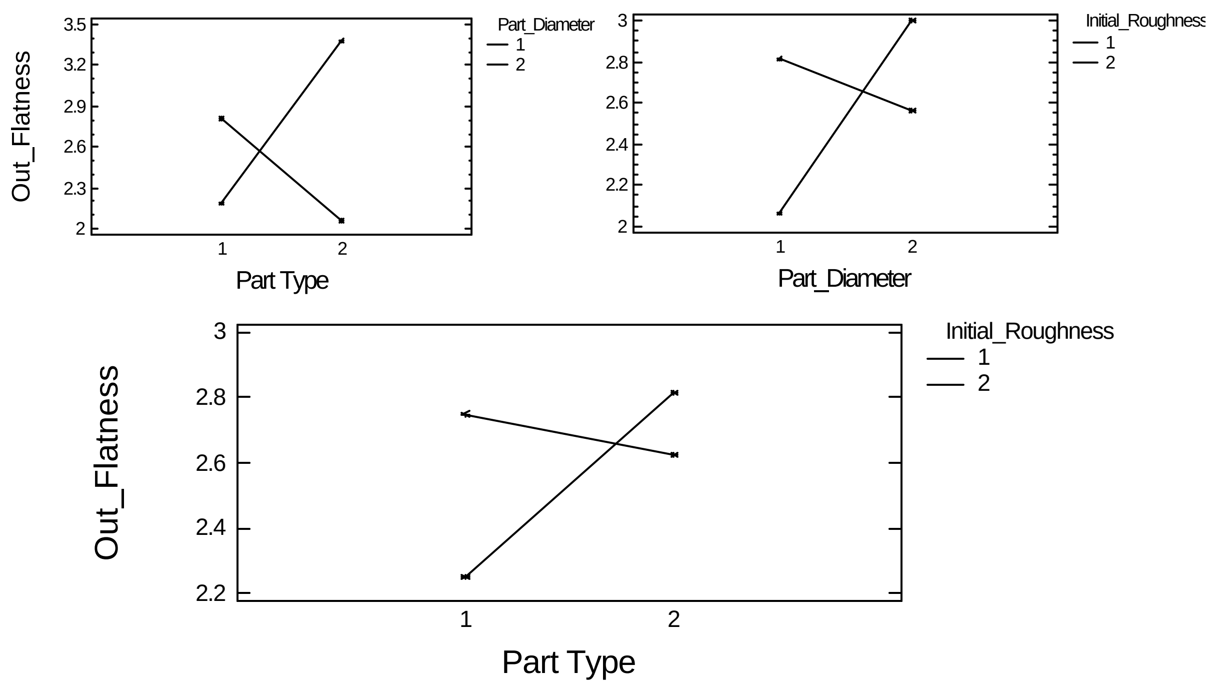



Figure 29 Interaction Plots of the Significant Pairs with respect to *Surface Flatness* (Mechanical Lapping)

Table 25 ANOVA Results of Fitting a Multiple Linear Regression Model to Describe the Relationship between *Surface Flatness* and Significant Independent Variables (Mechanical Lapping)

| Source | Sum of Squares | Df | Mean Square | F-Ratio | P-Value |
|---|---|---|---|---|---|
| Model | 12.7969 | 6 | 2.13281 | 17.37 | 0.0000 |
| Residual | 3.07031 | 25 | 0.122813 | | |
| Total (Corr.) | 15.8672 | 31 | | | |

R-squared = 80.6499 percent
R-squared (adjusted for d.f.) = 76.0059 percent

The equation below is the best regression model with respect to its highest adjusted $R^2$ comparing with other possible models.

```
Out_Flatness = 10.5781 - 3.71875*Part Type - 4.34375*Part_Diameter
               - 2.96875*Initial_Roughness
               + 1.9375*Part Type*Part_Diameter
               + 0.6875*Part Type*Initial_Roughness
               + 1.1875*Part_Diameter*Initial_Roughness
```

Since the P-value of the above model in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level. The R-squared statistic indicates that the model as fitted explains 80.65% of the variability in *Surface Flatness*. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is also relatively high (76%). In sum, *Part Type*, *Part Diameter* and interactions of *Part Type*Part Diameter*, *Part Type*Initial Roughness*, and *Part Diameter*Initial Roughness* more or less have statistically significant effects on *Surface Flatness.* However, *Part Diameter* is statistically significant by all test techniques, and thus the most important parameter with respect to *Surface Flatness*.

Table 26 Summary of Significant Effects with respect to Different Statistical Analyses (Mechanical Lapping – Surface Flatness)

| **Significant Effects** | **Test** | **Significance Level (a )** | **Statistics*** |
|---|---|---|---|
| Part Diameter | ANOVA<br>Regression | 0.05<br>0.05 | 0.0187<br>0.0187 |
| Part Type*Part Diameter | ANOVA<br>Regression | 0.01<br>0.01 | 0.0000<br>0.0000 |
| Part Type*Initial Roughness | ANOVA<br>Regression | 0.05<br>0.05 | 0.0187<br>0.0187 |
| Part Diameter*Initial Roughness | ANOVA<br>Regression | 0.01<br>0.01 | 0.0007<br>0.0007 |
| Part Type, Part Diameter, Initial Roughness, Part Type*Initial Roughness, Part Type*Part Diameter, Part Diameter*Initial Roughness | Regression Model | 0.01 | 0.000(model)<br>Adjusted-$R^2$ = 76.01% |

*Statistics are p-value, unless otherwise indicated.

The results from data analysis of mechanical lapping experiments indicate that interactions of *Part Type* vs. *Part Diameter*, *Part Diameter* vs. *Initial Roughness*, and *Part Type* vs. *Initial Roughness* have statistically significant effects on *Surface Flatness*. The results indicate that lapping discs with wider seats (larger diameters) results in better surface flatness compared to lapping discs with narrower seats (smaller diameters). This indication does not directly follow the rule of thumb that lapping discs with wider seats or larger diameters tend to decrease the ability to obtain better surface flatness. This could be the result of experiment variations, e.g. differences in the initial surface flatness of parts. On the other hand, the results indicate that lapping nozzles with narrower seats (smaller diameters) results in better surface flatness comparing to lapping nozzles with wider seats (larger diameters), which follows the theory previously mentioned. However, the effect of *Part Type* on *Surface Flatness* is somewhat smaller for lapping narrower (smaller) seats. The results indicate that lapping narrower/smaller seats with worse initial roughness results in better surface flatness compared to lapping wider/larger seats with better initial roughness. On the other hand, the results indicate that lapping wider/larger seats with better initial roughness result in better surface flatness comparing to lapping narrower/smaller seats with worse initial roughness. This situation may be the result of some experimental variations, e.g. differences in the initial surface flatness of parts or correlation of *Initial Roughness* and *Surface Flatness* before lapping. However, the effect of *Part Diameter (Seat Width)* on *Surface Flatness* is smaller for lapping parts with better initial roughness. This indication can be explained by the rule of thumb that lapping parts with poor surface roughness requires more time and effort, thus, faces more process variation with respect to surface flatness since there is more material to be removed. The results indicate that lapping discs with poorer initial roughness result in better surface flatness comparing to lapping discs with better surface roughness. On the other hand, lapping nozzles with better initial roughness results in better surface flatness compared to lapping nozzles with poorer initial roughness. This could be a result from experiment variations, e.g. differences in the initial surface flatness of parts. However, the effect of *Initial Roughness* on *Surface Flatness* is smaller for lapping nozzle seats than lapping discs.

### 6.3.3 Surface Roughness

This section shows the results of statistical analyses with respect to *Surface Roughness*. The explanation of findings after consolidating results from different statistical analyses can be found at the end of this section. (See Table 30 for a brief summary of significant effects found from different statistical analyses.)

Table 27 Analysis of Variance Table for *Surface Roughness* (Mechanical Lapping)

| Source | Sum of Squares | Df | Mean Square | F-Ratio | P-Value |
|---|---|---|---|---|---|
| MAIN EFFECTS | | | | | |
| A:Part Type | 1.64258 | 1 | 1.64258 | 8.33 | 0.0162 |
| B:Part_Diameter | 53.1738 | 1 | 53.1738 | 269.55 | 0.0000 |
| C:RPM | 0.0175781 | 1 | 0.0175781 | 0.09 | 0.7714 |
| D:Initial_Roughness | 0.861328 | 1 | 0.861328 | 4.37 | 0.0632 |
| E:Grit_Rough | 0.158203 | 1 | 0.158203 | 0.80 | 0.3915 |
| F:Grit_Finish | 0.705078 | 1 | 0.705078 | 3.57 | 0.0880 |
| INTERACTIONS | | | | | |
| AB | 22.3613 | 1 | 22.3613 | 113.36 | 0.0000 |
| AC | 1.0332 | 1 | 1.0332 | 5.24 | 0.0451 |
| AD | 1.64258 | 1 | 1.64258 | 8.33 | 0.0162 |
| AE | 0.705078 | 1 | 0.705078 | 3.57 | 0.0880 |
| AF | 0.0957031 | 1 | 0.0957031 | 0.49 | 0.5020 |
| BC | 1.0332 | 1 | 1.0332 | 5.24 | 0.0451 |
| BD | 1.64258 | 1 | 1.64258 | 8.33 | 0.0162 |
| BE | 1.87695 | 1 | 1.87695 | 9.51 | 0.0115 |
| BF | 0.0488281 | 1 | 0.0488281 | 0.25 | 0.6296 |
| CD | 2.12695 | 1 | 2.12695 | 10.78 | 0.0082 |
| CE | 0.439453 | 1 | 0.439453 | 2.23 | 0.1664 |
| CF | 0.861328 | 1 | 0.861328 | 4.37 | 0.0632 |
| DE | 2.67383 | 1 | 2.67383 | 13.55 | 0.0042 |
| DF | 1.0332 | 1 | 1.0332 | 5.24 | 0.0451 |
| EF | 2.67383 | 1 | 2.67383 | 13.55 | 0.0042 |
| RESIDUAL | 1.97266 | 10 | 0.197266 | | |
| TOTAL (CORRECTED) | 98.7793 | 31 | | | |

The results from the ANOVA table indicate that *Part Type* and *Part Diameter (Seat Width)* have main effects on *Surface Roughness* at 95% significant level. The interactions of *Part Type* vs. *Part Diameter*, *Part Type* vs. *RPM, Part Type* vs. *Initial Roughness*, *Part Diameter* vs. *RPM, Part Diameter* vs. *Initial Roughness*, *Part Diameter* vs. *Grit Rough*, *RPM* vs. *Initial Roughness*, *Initial Roughness* vs. *Grit Rough*, *Initial Roughness* vs. *Grit Finish*, and *Grit Rough* vs. *Grit Finish* are significant with respect to *Surface Flatness* at 95% significant level. Since the $2_{VI}^{6-1}$ design was used, because of aliasing, these effects are really *A+BCDEF*, *B+ACDEF*, *AB+CDEF*, *AC+BDEF*, *AD+BCEF*, *BC+ADEF*, *BD+ACEF*, *BE+ACDF*, *CD+ABEF*, *DE+ABCF*, *DF+ABCE*, and *EF+ABCD* (see Table 58 in Appendix B for alias relationships). However, since it seems plausible that four-factor and higher interactions are negligible, it is safe to conclude that *Part Type(A), Part Diameter(B), Part Type* vs. *Part Diameter(AB), Part Type vs. RPM(AC*), *Part Type* vs. *Initial Roughness(AD)*, *Part Diameter* vs. *RPM(BC), Part Diameter* vs. *Initial Roughness(BD), Part Diameter* vs. *Grit Rough(BE), RPM* vs. *Initial Roughness(CD), Initial Roughness* vs. *Grit Rough(DE), Initial Roughness* vs. *Grit Finish(DF),* and *Grit Rough* vs. *Grit Finish(EF)* are important effects.

The following Table 28 summarizes the p-values from Kruskal-Wallis test of *Surface Roughness* vs. other controllable parameters. The results indicate that different levels of *Part Diameter* are statistically different with respect to *Surface Roughness*.

Table 28 P-values from Kruskal-Wallis Test for *Surface Roughness* vs. Other Controllable Parameters (Mechanical Lapping)

| **Test Parameters** | **P-value** |
|---|---|
| Roughness vs. Part Type | 0.775988 |
| *Roughness vs. Part Diameter* | *0.0000300078* |
| Roughness vs. RPM | 0.662611 |
| Roughness vs. Initial Roughness | 0.352612 |
| Roughness vs. Grit Rough | 0.954617 |
| Roughness vs. Grit Finish | 0.761493 |

The following Figure 30 illustrates mean plots of *Surface Roughness* vs. different levels of other controllable parameters.

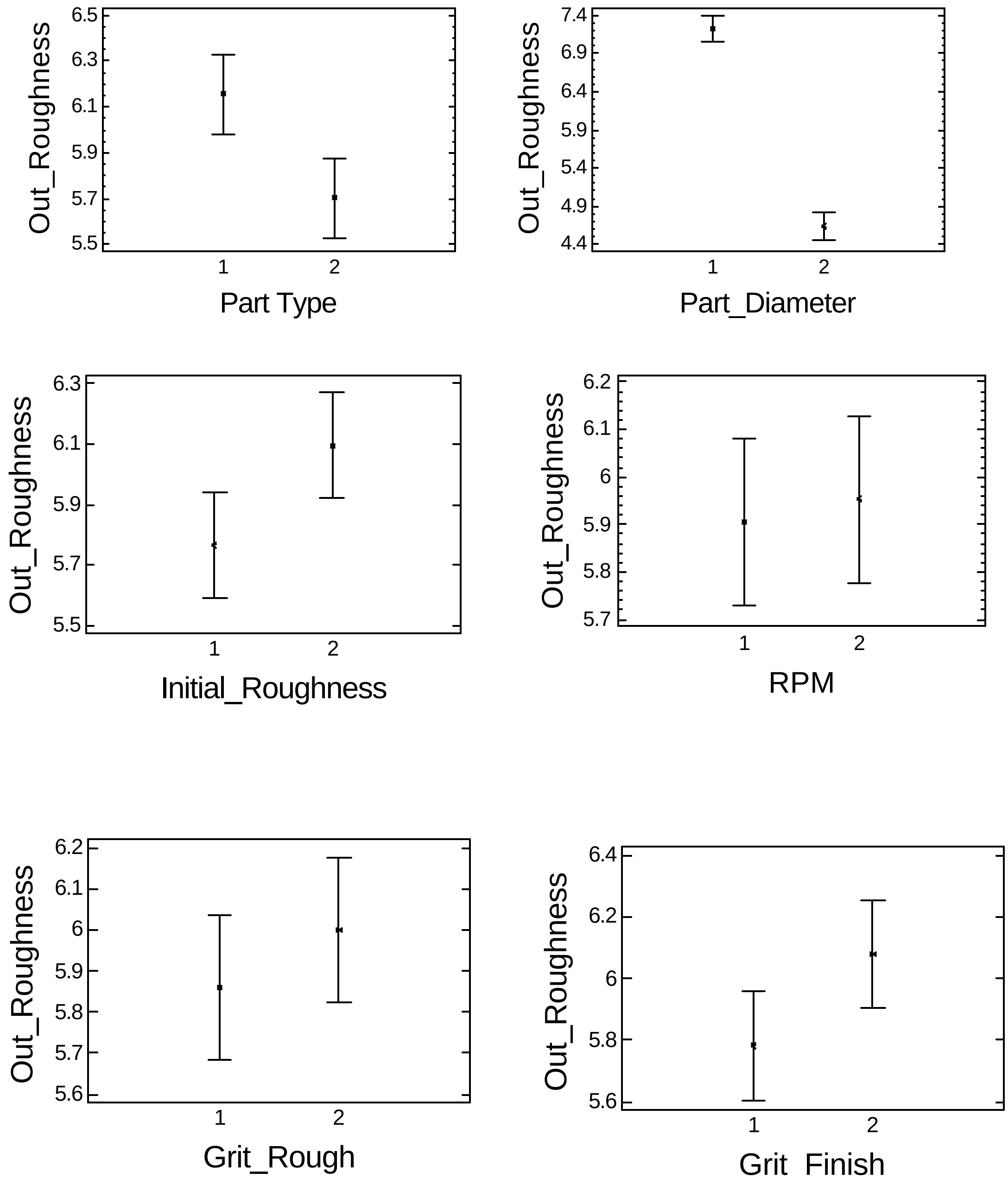



Figure 30 Mean Plots of *Surface Roughness* vs. Other Controllable Parameters [Mechanical Lapping]

Mean plots in Figure 30 indicate the following remarks:

- For different levels of *Part Type*, the mean plot indicates that the higher the *Part Type*, the lower the *Surface Roughness*.
- For different levels of *Part Diameter*, the mean plot clearly indicates that the higher the *Part Diameter*, the lower the *Surface Roughness*.
- For different levels of *Initial Roughness*, the mean plot indicates that the higher the *Initial Roughness*, the higher the *Surface Roughness.*
- For different levels of *RPM*, the mean plot indicates that, for different level of *RPM* there is no different in term of Surface *Roughness*.
- For different levels of *Grit Rough*, the mean plot indicates that the higher the *Grit Rough*, the slightly higher the *Surface Roughness.*
- For different levels of *Grit Finish*, the mean plot indicates that the higher the *Grit Finish*, the higher the *Surface Roughness.*

The ANOVA results in Table 27 also indicate that ten interactions are statistically significant with respect to *Surface Roughness*. The following Figure 31 shows interaction plots of the significant pairs.

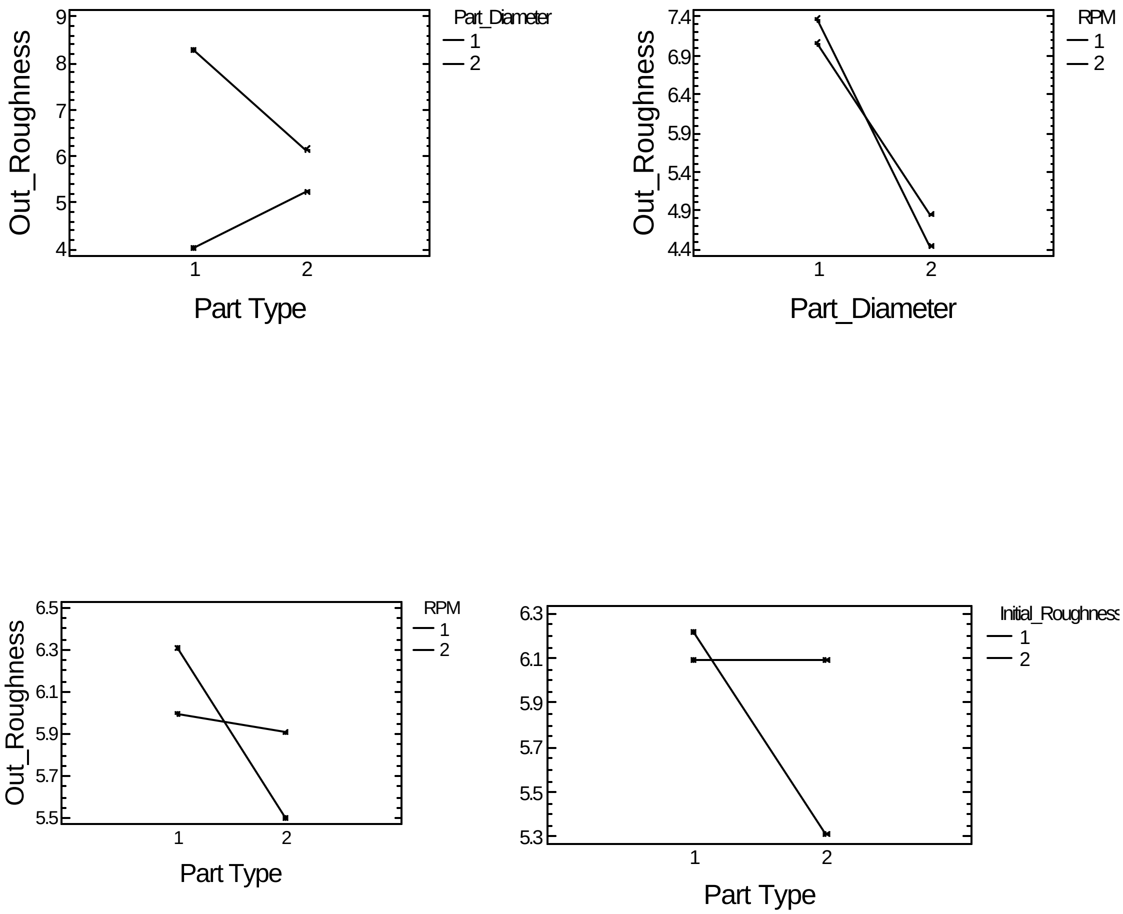



Figure 31 Interaction Plots of the Significant Pairs with respect to *Surface Roughness* [Mechanical Lapping]

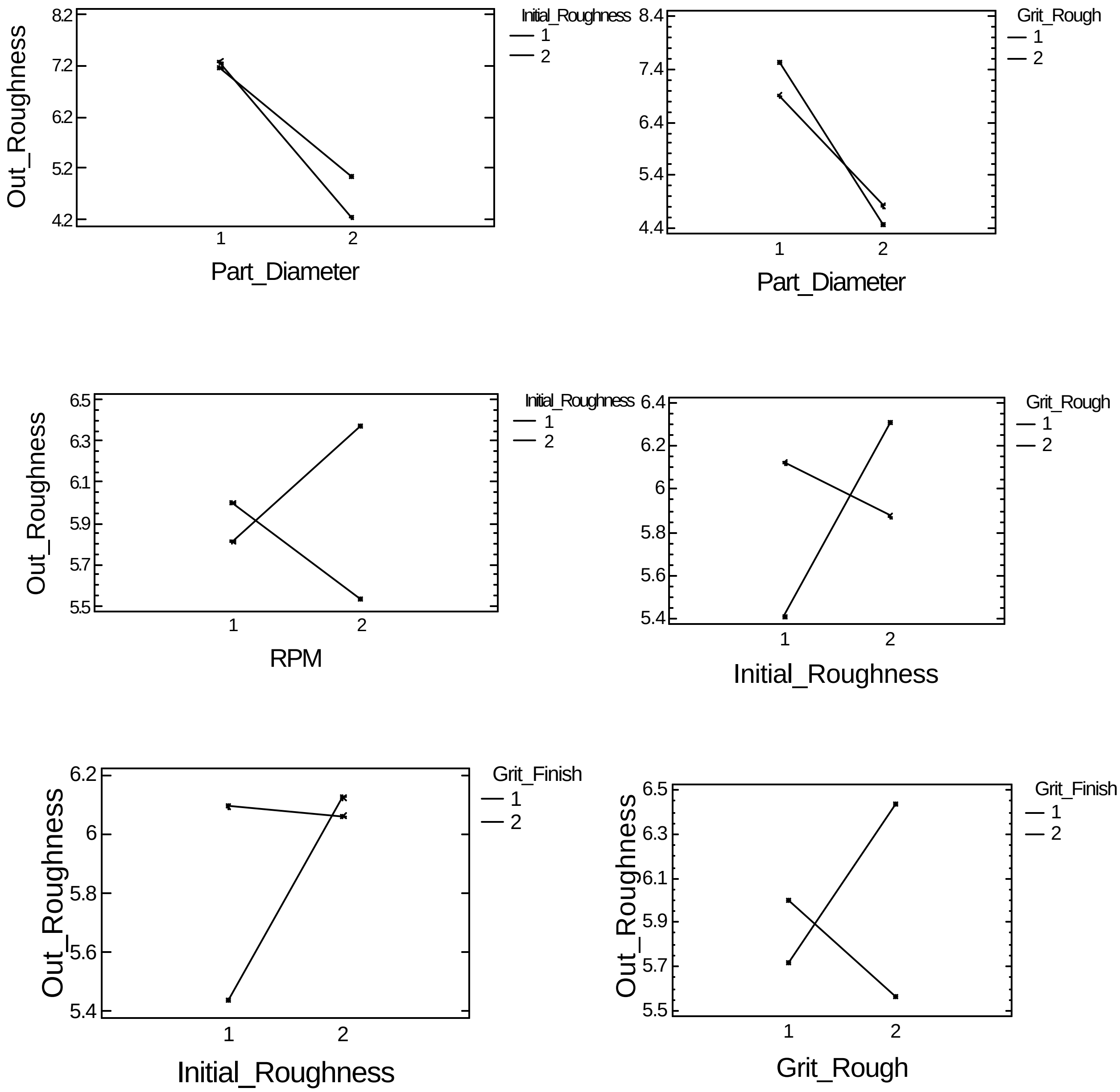



Figure 31 Interaction Plots of the Significant Pairs with respect to *Surface* Roughness [Mechanical Lapping] (continued)

Table 29 ANOVA Results of Fitting a Multiple Linear Regression Model to Describe the Relationship between *Surface Roughness* and Significant Independent Variables (Mechanical Lapping)

| Source | Sum of Squares | Df | Mean Square | F-Ratio | P-Value |
|---|---|---|---|---|---|
| Model | 88.3994 | 8 | 11.0499 | 24.48 | 0.0000 |
| Residual | 10.3799 | 23 | 0.451298 | | |
| Total (Corr.) | 98.7793 | 31 | | | |

R-squared = 89.4919 percent
R-squared (adjusted for d.f.) = 85.8369 percent

The equation below is the best regression model with respect to its highest adjusted $R^2$ compared with other possible models.

```
Out_Roughness = 19.6761 - 6.97004*Part Type - 9.09504*Part_Diameter
                + 3.34375*Part Type*Part_Diameter
                + 1.00086*Part Type*Initial_Roughness
                + 1.00086*Part_Diameter*Initial_Roughness
                - 0.965489*Initial_Roughness*Grit_Rough
                - 0.827989*Initial_Roughness*Grit_Finish
                + 1.04856*Grit_Rough*Grit_Finish
```

Since the P-value of the above model in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level. The R-squared statistic indicates that the model as fitted explains 89.5% of the variability in *Surface Roughness.* The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is also high (86%). In sum, *Part Type, Part Diameter* and interactions of *Part Type*Part Diameter*, *Part Type*Initial Roughness, Part Diameter*Initial Roughness, Initial Roughness*Grit Rough, Initial Roughness*Grit Finish,* and *Grit Rough*Grit Finish* have statistically significant effects on *Surface Roughness.* However, *Part Diameter* is statistically significant by all test techniques, and thus the most important parameter with respect to *Surface Roughness*.

Table 30 A Summary of Significant Effects with respect to Different Statistical Analyses (Mechanical Lapping – Surface Roughness)

| **Significant Effects** | **Test** | a **Level** | **Statistics***  |
|---|---|---|---|
| Part Type | ANOVA, Regression | 0.05 | 0.0162 |
| Part Diameter | ANOVA, Regression<br>Kruskal-Wallis | 0.01<br>0.01 | 0.0000<br>0.00003 |
| Part Type*Part Diameter | ANOVA, Regression | 0.01 | 0.0000 |
| Part Type*RPM | ANOVA, Regression | 0.05 | 0.0451 |
| Part Type*Initial Roughness | ANOVA, Regression | 0.05 | 0.0162 |
| Part Diameter*RPM | ANOVA, Regression | 0.05 | 0.0454 |
| Part Diameter*Initial Roughness | ANOVA, Regression | 0.05 | 0.0162 |
| Part Diameter*Grit Rough | ANOVA, Regression | 0.05 | 0.0115 |
| RPM*Initial Roughness | ANOVA, Regression | 0.01 | 0.0082 |
| Initial Roughness*Grit Rough | ANOVA, Regression | 0.01 | 0.0042 |
| Initial Roughness*Grit Finish | ANOVA, Regression | 0.05 | 0.0451 |
| Grit Rough*Grit Finish | ANOVA, Regression | 0.01 | 0.0042 |
| Part Type, Part Diameter, Part Type*Initial Roughness, Part Type*Part Diameter, Part Diameter*Initial Roughness, Initial Roughness*Grit Rough, Initial Roughness*Grit Finish, Grit Rough*Grit Finish | Regression Model | 0.01 | 0.000(model)<br>Adjusted-$R^2$ = 85.84% |

*Statistics are p-value, unless otherwise indicated.

As in the case of manual lapping, *Surface Roughness*, obtained from mechanical lapping, is generally related to Initial Roughness and *Grit Size*. Since the speed of rotation is involved in mechanical lapping, *Surface Roughness* is also theoretically related to the levels of rotation speed, measured in revolution per minute (*RPM*); the faster the speed, the more chance of deteriorating the surface roughness. Thus, we can conclude that lapping is theoretically a very low-speed finishing process after all.

The results from data analysis of mechanical lapping experiments indicate that interactions of *Part Type* vs. *Part Diameter, Part Diameter* vs. *Initial Roughness, Part Type* vs. *Initial Roughness, Initial Roughness* vs. *Grit Rough, Initial Roughness* vs. *Grit Finish, and Grit Rough* vs. *Grit Finish* have statistically significant effects on *Surface Roughness*. The results indicate that lapping discs with wider seats (larger diameters) results in better surface roughness compared to lapping discs with narrower seats (smaller diameters). The same trend also holds when lapping nozzles. However, the effect of *Part Diameter (Seat Width)* on *Surface Roughness* is somewhat smaller for lapping nozzles. The results indicate that lapping discs with better initial roughness results in slightly worse surface roughness compared to lapping discs with better initial roughness. On the other hand, the results indicate that lapping nozzles with better initial roughness results in much better surface roughness compared to lapping nozzles with poorer initial roughness. This could be a result of experiment variations, e.g. acceptable surface roughness after lapping is usually represented in range, thus, the lapping operator might have stopped lapping at different levels of surface roughness (within the acceptable range). However, the effect of *Initial Roughness* on *Surface Roughness* is much smaller when lapping parts with worse initial roughness. The results indicate that lapping narrower/smaller seats with different levels of initial roughness does not make much difference in term of surface roughness obtained. On the other hand, the results indicate that lapping wider/larger seats with better initial roughness results in better surface roughness compared to lapping wider/larger seats with worse initial roughness (which follows the rule of thumb). However, the effect of *Initial Roughness* on *Surface Roughness* is smaller for lapping parts with smaller widths/diameters.

The results indicate that lapping parts with better initial roughness using grit # 220 for rough lap gives better surface roughness, when compared to lapping parts with grit # 320. Again, this indication might be a result of process variation, e.g. roughness measurement or a 3-order interaction among *Initial Roughness, Grit Rough,* and *Grit Finish.* On the other hand, the results indicate that lapping parts with poorer initial roughness using grit # 320 for rough lap gives better surface roughness, comparing with lapping parts using grit # 220. Abrasive grains in grit #220 are very coarse and can cause more damage to the surface. However, the effect of *Initial Roughness* on *Surface Roughness* is much smaller when lapping parts with grit # 320. This indication can also be explained by considering abrasive grain size. Grit # 320 has finer grain, thus decreasing the chance of deteriorating the lapping surface. The results indicate that lapping parts with better initial roughness using grit # 500 for finish lap gives better surface roughness, comparing with lapping parts with grit # 900. On the other hand, the results indicate that lapping parts with poorer initial roughness using grit # 500 or # 900 for rough lap does not make that much of a difference in term of surface roughness.

Again, this indication might be a result of process variation, e.g. surface roughness measurement. However, the effect of *Initial Roughness* on *Surface Roughness* is much smaller when lapping parts with grit # 900. This indication can also be explained by considering abrasive grain size. Grit # 900 has very fine grains and removes very small amounts of material, thus making a small difference in term of surface roughness after lapping without spending significant time. As in the general rule of thumb, the results indicate that there is an interaction between *Grit Rough* and *Grit Finish*. The results indicate that using a combination of grit # 220 and # 900 for rough and finish lapping gives better surface roughness, compared to using a combination of #220 and # 500. Using a combination of grit # 320 and # 500 for rough and finish lapping gives better surface roughness, compared with using a combination of # 320 and # 900. In addition, comparing with grit # 320, using grit # 220 as grit rough results in smaller variation with respect to surface roughness. The results from data analysis also indicate that *Surface Roughness* and *MRR* are positively correlated.

### 6.3.4 Material Removal Rate (MRR)

This section shows the results from statistical analyses with respect to *MRR.* The explanation of findings after consolidating results from different statistical analyses can be found at the end of this section. (See Table 33 for a brief summary of significant effects found from different statistical analyses.)

Table 31 Analysis of Variance for Material Removal Rate [MRR] (Mechanical Lapping)

| Source | Sum of Squares | Df | Mean Square | F-Ratio | P-Value |
|---|---|---|---|---|---|
| MAIN EFFECTS | | | | | |
| A:Part Type | 0.0636799 | 1 | 0.0636799 | 3.44 | 0.0931 |
| B:Part_Diameter | 0.278575 | 1 | 0.278575 | 15.07 | 0.0030 |
| C:RPM | 0.00136112 | 1 | 0.00136112 | 0.07 | 0.7916 |
| D:Initial_Roughness | 0.00472149 | 1 | 0.00472149 | 0.26 | 0.6242 |
| E:Grit_Rough | 0.0556695 | 1 | 0.0556695 | 3.01 | 0.1133 |
| F:Grit_Finish | 0.0097965 | 1 | 0.0097965 | 0.53 | 0.4833 |
| INTERACTIONS | | | | | |
| AB | 0.508914 | 1 | 0.508914 | 27.53 | 0.0004 |
| AC | 0.0101069 | 1 | 0.0101069 | 0.55 | 0.4766 |
| AD | 0.0591594 | 1 | 0.0591594 | 3.20 | 0.1039 |
| AE | 0.0000548628 | 1 | 0.0000548628 | 0.00 | 0.9576 |
| AF | 0.00219288 | 1 | 0.00219288 | 0.12 | 0.7377 |
| BC | 0.062384 | 1 | 0.062384 | 3.37 | 0.0961 |
| BD | 0.0182357 | 1 | 0.0182357 | 0.99 | 0.3440 |
| BE | 0.0252844 | 1 | 0.0252844 | 1.37 | 0.2693 |
| BF | 0.0307954 | 1 | 0.0307954 | 1.67 | 0.2258 |
| CD | 0.150084 | 1 | 0.150084 | 8.12 | 0.0173 |
| CE | 0.00110803 | 1 | 0.00110803 | 0.06 | 0.8115 |
| CF | 0.00287093 | 1 | 0.00287093 | 0.16 | 0.7018 |
| DE | 0.0250264 | 1 | 0.0250264 | 1.35 | 0.2716 |
| DF | 0.0614689 | 1 | 0.0614689 | 3.33 | 0.0982 |
| EF | 0.163378 | 1 | 0.163378 | 8.84 | 0.0140 |
| RESIDUAL | 0.184848 | 10 | 0.0184848 | | |
| TOTAL (CORRECTED) | 1.71971 | 31 | | | |

The results from ANOVA indicate that *Part Diameter (Seat Width)* and interactions between *Part Type* and *Part Diameter*, *RPM* and *Initial Roughness*, as well as *Grit Rough* and *Grit Finish* have effects on *MRR* at 95% significant level. Since the

$2_{VI}^{6-1}$ design was used and because of aliasing, these effects are really *B+ACDEF*, *AB+CDEF*, *CD+ABEF*, and *EF+ABCD.* However, since it seems plausible that four-factor and higher interactions are negligible, it is safe in concluding that *Part Diameter(B)*, *Part Type* vs. *Part Diameter(AB)*, *RPM* vs. *Initial Roughness(CD)*, and *Grit Rough* vs. *Grit Finish(EF)* are important effects.

The following Figure 32 shows mean plots of *Material Removal Rate* vs. different levels of other controllable parameters.

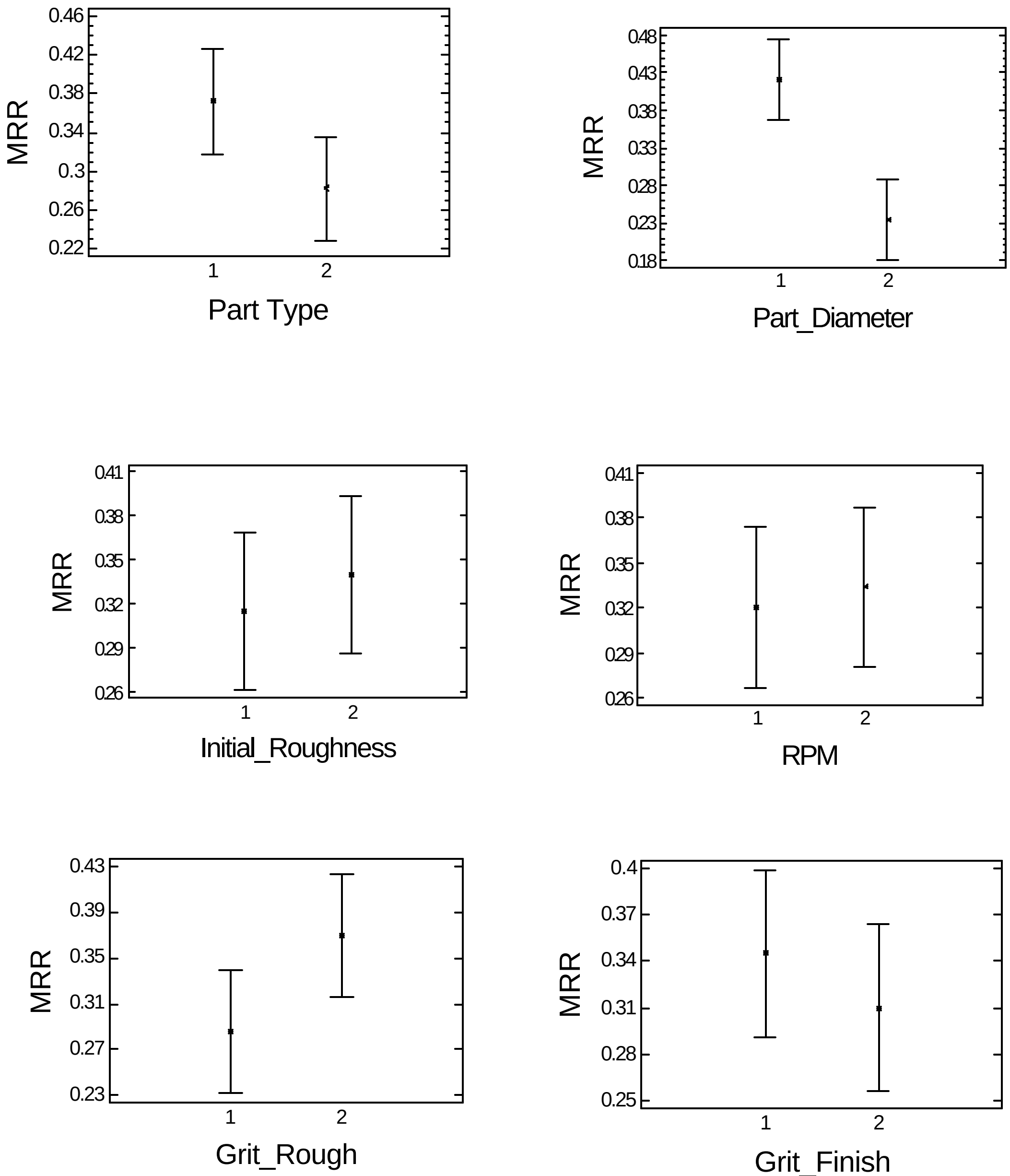



Figure 32 Mean Plots of *Material Removal Rate* vs. Other Controllable Parameters (Mechanical Lapping)

Mean plots in Figure 32 indicate the following remarks:

- For different levels of *Part Type*, the mean plot indicates that the higher the *Part Type*, the lower the *MRR.*
- For different levels of *Part Diameter*, the mean plot clearly indicates that the higher the *Part Diameter,* the lower the *MRR.*
- For different levels of *Initial Roughness*, the mean plot indicates that the higher the *Initial Roughness*, the slightly higher the *MRR.*
- For different levels of *RPM,* the mean plot indicates that, for different level of *RPM* there is no different in term of *MRR.*
- For different levels of *Grit Rough*, the mean plot indicates that the higher the *Grit Rough*, the higher the *MRR.*
- For different levels of *Grit Finish*, the mean plot indicates that the higher the *Grit Finish*, the lower the *MRR.*

The ANOVA results in Table 31 indicate that there are three significant interactions: *Part Type* and *Part Diameter*, *RPM* and *Initial Roughness*, as well as *Grit Rough* and *Grit Finish*. Figure 33 shows interaction plots of the three significant interactions.

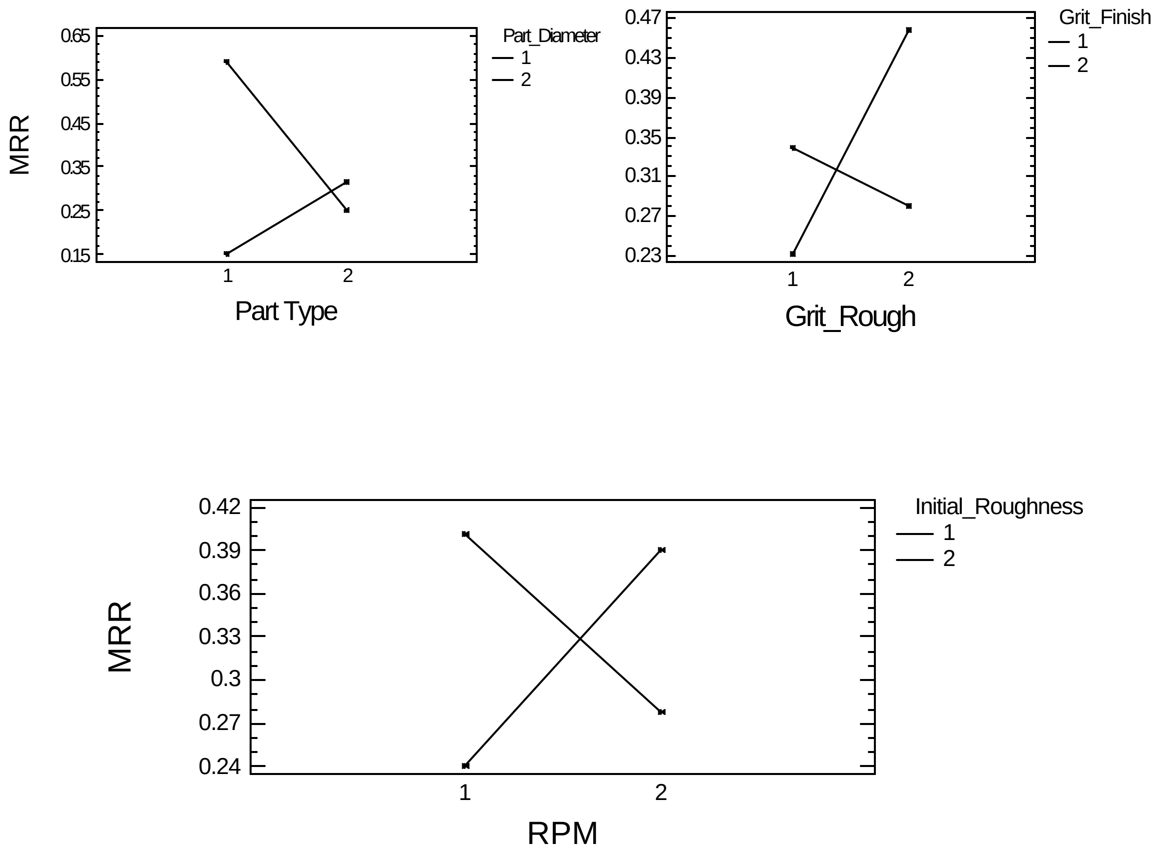



Figure 33 Interaction Plots of the three Significant Interaction Effects with respect to *MRR* (Mechanical Lapping)

Scatter plots do not indicate any major concern regarding the inequality of the variances. Plot of residuals versus predicted *MRR* does not indicate any problem regarding the violation of the normality assumption and equality of variance.

Table 32 ANOVA Results of Fitting a Multiple Linear Regression Model to Describe the Relationship between *MRR* and Significant Independent Variables (Mechanical Lapping)

```
-------------------------------------------------------------
Source     Sum of Squares  Df  Mean Square  F-Ratio  P-Value
-------------------------------------------------------------
Model          1.38332     10   0.138332     8.64    0.0000
Residual      0.336395     21   0.0160188
-------------------------------------------------------------
Total (Corr.)  1.71971     31

R-squared = 80.4389 percent
R-squared (adjusted for d.f.) = 71.1241 percent
```

The equation below is the best regression model with respect to its highest adjusted $R^2$ comparing with other possible models.

```
MRR = 1.91863 - 1.11459*Part Type - 1.27843*Part_Diameter
      + 0.487935*Grit_Finish + 0.504438*Part Type*Part_Diameter
      + 0.179142*Part Type*Initial_Roughness
      + 0.223444*Part_Diameter*RPM
      - 0.219952*RPM*Initial_Roughness
      + 0.224368*Initial_Roughness*Grit_Rough
      - 0.168158*Initial_Roughness*Grit_Finish
      - 0.180461*Grit_Rough*Grit_Finish
```

Since the P-value of the above model in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level. The R-squared statistic indicates that the model as fitted explains 80.44% of the variability in *MRR.* The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is also relatively high (71.1%). In sum, *Part Type, Part Diameter, Grit Finish* and interactions of *Part Type*Part Diameter*, *Part Type*Initial Roughness*, *Part Diameter*RPM, RPM*Initial Roughness, Initial Roughness*Grit Rough, Initial Roughness*Grit Finish,* and *Grit Rough*Grit Finish* more or less have statistically significant effects on *MRR.* However, *Part Diameter* is statistically significant by all test techniques, and thus the most important parameter with respect to *MRR*.

Table 33 A Summary of Significant Effects with respect to Different Statistical Analyses (Mechanical Lapping – MRR)

| **Significant Effects** | **Test** | a **Level** | **Statistics*** |
|---|---|---|---|
| Part Diameter | ANOVA, Regression | 0.01 | 0.0030 |
| Part Type*Part Diameter | ANOVA, Regression | 0.01 | 0.0004 |
| RPM*Initial Roughness | ANOVA, Regression | 0.05 | 0.0173 |
| Grit Rough*Grit Finish | ANOVA, Regression | 0.05 | 0.0140 |
| Part Type, Part Diameter, Grit Finish Part Type*Initial Roughness, Part Type*Part Diameter, Part Diameter*RPM, RPM*Initial Roughness, Initial Roughness*Grit Rough, Initial Roughness*Grit Finish, Grit Rough*Grit Finish | Regression Model | 0.01 | 0.000(model) Adjusted-$R^2$ = 71.12% |

*Statistics are p-value, unless otherwise indicated.

As in the case of manual lapping, *MRR*, obtained from mechanical lapping, is generally related to *Part Diameter (Seat Width)* and *Grit Size*. Since the speed of rotation is an important variable in the process of mechanical lapping, *MRR* is generally related to the levels of rotation speed, measured in revolution per minute (RPM); the faster the speed, the more amount of material removed in a time unit, thus higher *MRR*.

The results indicate that lapping discs with wider seats (larger diameters) results in lower *MRR*, compared with lapping discs with narrower seats (smaller diameters). On the other hand, the results indicate that lapping nozzles does not make that much of a difference in term of part diameter (seat width) with respect to *MRR*. Generally, *MRR* should be higher in the case of lapping wider seats (larger diameters). The indication from the experiments may be a result of existing of high-order interactions. Grit size generally plays an important role in *MRR*. The results indicate that using a combination of grits # 220 and # 900 for rough and finish lapping respectively results in a higher *MRR*, when compared to using a combination of # 220 and # 500. Using a combination of grit # 320 and # 500 for rough and finish lapping respectively results in higher *MRR*, comparing with using a combination of # 320 and # 900. This indication may be a result of unequal time spent on each grit #. In addition, compared to grit # 500, using grit # 900 as grit finish results in smaller variation with respect to surface roughness. The results indicate that, at a lower speed of rotation, lapping parts with better initial roughness results in lower *MRR*, comparing with lapping parts with poorer initial roughness, which follows the rules of thumb. On the other hand, the results indicate that, at higher speeds of rotation, lapping parts with worse initial roughness results in lower *MRR*, comparing with lapping parts with better initial roughness. This indication may be a result of process variation, e.g. high speed of rotation increases process error and requires re-work during the process. The results from data analysis also indicate that *MRR* and *Surface Roughness* are positively correlated.

### 6.4 Implication from Manual and Mechanical Lapping Experiments

The results from data analyses indicate that, in general, *Part Type*, *Part Diameter*, and *Initial Roughness* are significant parameters with respect to all responses (*Surface Flatness*, *Surface Roughness*, and *MRR*) for both manual and mechanical lapping. However, *Grit Size* also plays an important role in case of mechanical lapping.

The results from data analyses also indicate that there are many more significant interaction effects revealed from mechanical lapping experiments compared to those from manual lapping experiments. In addition, compared to those for manual lapping, all best-fit regression models for mechanical lapping contain higher adjusted-$R^2$, especially the regression model for *MRR*. This means that the critical process parameters in mechanical lapping have a stronger linear relationship with the process outcomes, compared to those in manual lapping. These indications may be explained by considering the difference of manual and mechanical lapping in term of process variation. In case of mechanical lapping, using the lapping tool, more process parameters can be controlled, though they may not be able to be quantified, e.g. lapping pressure, speed of rotation, and stabilization of workpiece or lap ring. These process control parameters are generally applied with high uniformity during the mechanical lapping process, which results in less process variation due to human errors.

In term of lapping tool design, it was found from experiments that the orientation of the upper part was not flexible enough to allow the workpiece and lap ring surfaces to lay flat against each other without adjustment. At times, the workpiece became tilted after initial contact with the lap ring (the reciprocal was also true). Without proper pre-cautions, this may damage the workpiece and the lap ring surfaces. However, after conducting the experiments, the tool was re-modified for both the upper part and the base part, including the orientation of the upper part. A universal joint was used in place of a ball to better control the orientation of the upper part and minimize the previously mentioned problem. However, a more extensive study and test are required to ensure that the tool is functioning properly.

# 7.0 METHODOLOGY FOR ADVISORY SYSTEM DEVELOPMENT

The last objective of this research is to develop a protocol for lapping advisory system. In this chapter, the methodology will be explained in the context of advisory system development since it is the ultimate goal of this research effort. First, a framework of the advisory system was specified. The problem being solved, the users, the development tools, and the application context of such advisory system were explained. Secondly, the process of knowledge acquisition was carried out. The lapping process was thoroughly studied via literature review, a series of well-designed experiments, and extensive data analysis. Based on the type and availability of data and findings, tentative qualitative models and, consequently, conceptual knowledge base were developed with an application of fuzzy logic concepts. Finally, a preliminary flat lapping advisory system with applications on reconditioning valve discs and nozzle seats was proposed, tested, and validated.

## 7.1 Establishment of a Framework for the Advisory System

### 7.1.1 Setting the Domain Knowledge

In this research, the domain knowledge of interest is "flat-lapping" with application on reconditioning valve discs and nozzle seats. The reasons of choosing such domain knowledge are: (1) the process has become more critical especially in power generation, petroleum, and chemical industries, (2) the United States Products Co., which has been involved in the current research, has connections with a number of companies that can ease the process of knowledge acquisition, e.g. provide access to valve recondition facilities.

As mentioned earlier, lapping has been an art more than a science. Many factors contribute to the difference in quality of outcomes as a result of lapping carried out by different lapping operators, or even from the same lapping operators. The operators have to apply an appropriate combination of process parameters in order to achieve their desire outcomes. Some of the parameters of interest are shown in the following Table 34. These are parameters of interest in the early stage of this research. The process of identifying critical parameters will be discussed later on in this document.

Table 34 Parameters of Interest

| | |
|---|---|
| **Qualitative Parameters** | Abrasive Grit Size, Type of Abrasive, Type of Workpiece, Workpiece Material, Lapping Technique |
| **Quantitative Parameters** | Surface Finish, Flatness, Initial Roughness, Tolerance, Material Removal Rate, Time, Pressure, Speed of Rotation, Size Of Lap Ring/Block (e.g. Diameter, Weight) |

An inappropriate selection of the combination of these factors directly influences the finishing surface quality and may lead to a failure to meet the customers' requirements such as tolerance, surface parallelism, flatness, and/or finish. This will result in losing time and money for correction or re-manufacturing the parts. The proposed research to study the lapping process and to develop a protocol for advisory system will provide guidelines for standardizing this process and will help to overcome the problem. The ultimate goal of the advisory system, then, is to provide a system that enables novice operators in a manufacturing plant to access a standard set of guidelines and perform at a level of reliability equivalent to that of the plant's most skilled engineers and operators. More realistically, it is intended that the system will at least be able to capture some of the expert's skills for a focused set of problems and represent flat lapping in a more scientific form. However, due to many limitations in this research, the findings from this pilot study and system protocol will act as a sound guideline for further development of a more comprehensive advisory system.

### 7.1.2 Setting the Application Context for the Advisory System

In developing a good expert system, the application context of the system needs to be clarified and focused. Expert systems are designed to accomplish generic tasks on the basis of problem types as illustrated in Table 35 (adapted from Payne and McArthur[88]).

Table 35 Application areas for expert systems

| **Paradigm** | **Description** |
|---|---|
| Diagnosis | Determining problem causes |
| Repair | Determining solutions to diagnosed problems |
| Prediction | Determining outcomes to situations |
| Filtering | Eliminating unimportant information |
| Instruction | Interpreting user actions and providing guidance |
| Planning | Determining the type and order of actions |
| Design | Configuring objects with constraints |

The objectives of the proposed advisory system are to provide advice and to standardize the process of flat lapping. The proposed advisory system contains two main modules.

1. Lapping capability module provides a general guideline for flat lapping capability based on process characteristics. This module of the advisory system provides guidance on whether the application of interest is appropriate for lapping process.

2. In the second module, detailed guideline and process parameter values to perform the task are provided. This module of the advisory system provides the type, order of actions, and process control values for the operator. However, in this research, only a part of this second module (abrasive selection sub-module) was developed, due to some limitations, which will be discussed later in this document.

These modules make the system fall into the “instruction” and “planning” paradigms as described in the above Table 35. The advisory system provides advice and help in the process planning, which may be called computer aided process planning (CAPP) and advisory system.

### 7.1.3 Representative Advisory System Architecture

The following Figure 34 illustrates the proposed advisory system architecture. This architecture was developed based on the concepts written by Waterman.[89]

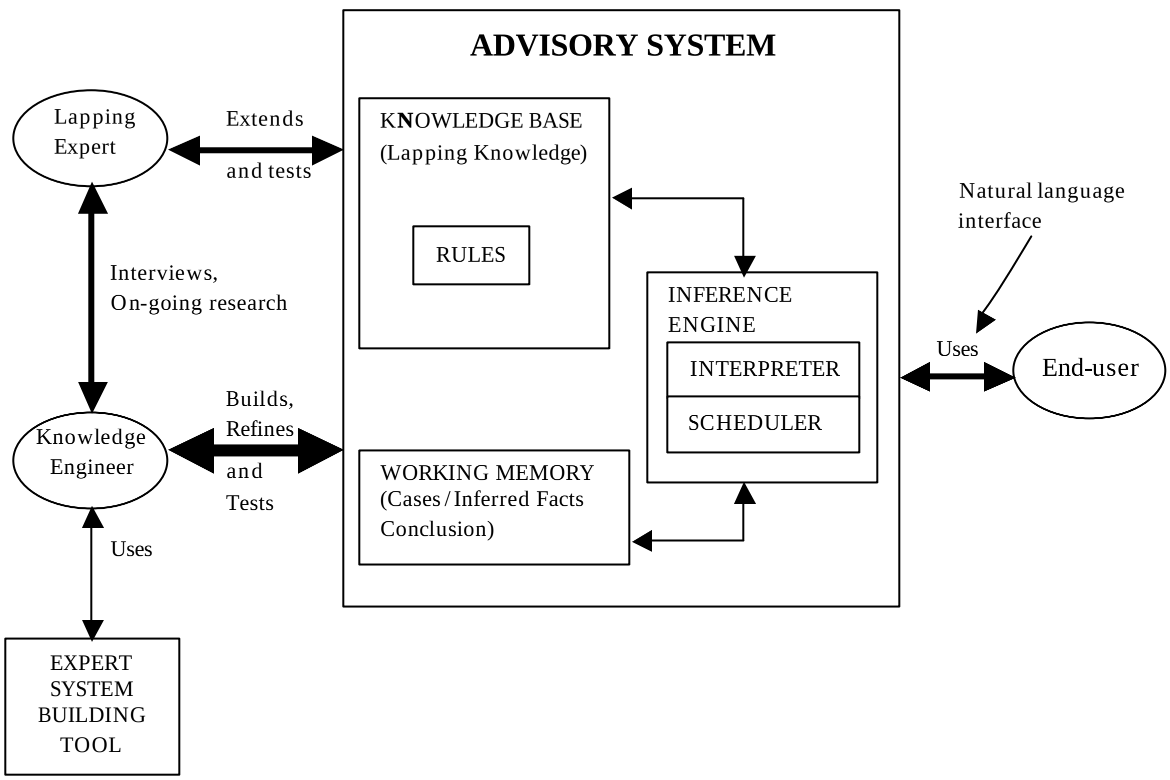



Figure 34 Generic architecture for the building an advisory system

The system architecture shows the main components of the advisory system (knowledge base, working memory, inference engine, and interface) and their interaction. Moreover, it provides a simplistic view of how the system is developed in relation to people and tools.

### 7.1.4 A Tentative Framework for the Development of a Knowledge Base

Figure 35 illustrates a simplified overall framework of knowledge base sub-modules in the proposed advisory system. There are four sub-modules in the system:

1) Process selection sub-module: This module is intended to provide the user advice by checking if "lapping" is the appropriate process for the particular application. Once users input all desired outcomes into the advisory system, it will determine whether lapping is applicable for the desired set of outcomes. The following are potential input and output variables:

*Output variable*

- Decision (yes---if lapping is a potential option, no---otherwise)

*Input variables*

- Expected Material Removal Rate (inch$^3$/minute)
- Desired Tolerance (μ-inch)
- Desired Surface Flatness (light-bands)
- Desired Surface Roughness (μ-inch)

2) Abrasive selection sub-module: This module is intended to provide a combination of recommended abrasive type and grit size(s) for a particular set of desired outcomes. The following are potential input and output variables:

*Output variables*

- Type of Abrasive
- Grit Size

*Input variables*

- Type of Workpiece Material and its Hardness (Rockwell C)
- Desired Surface Roughness (μm)
- Initial Surface Roughness (μm)
- Desired Surface Flatness (light-bands)
- Initial Surface Flatness (light-bands)
- Expected Material Removal Rate ($in^3$/min)

3) Lap ring selection sub-module: This module is intended to provide a combination of recommended lap-ring type, material, and size. The following are potential input and output variables:

*Output variables*

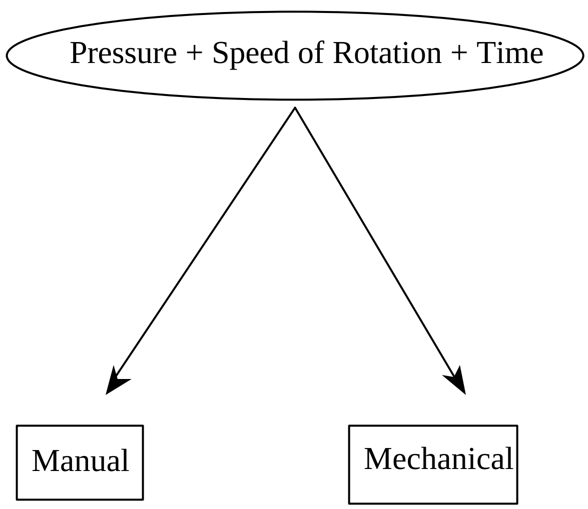
- Lap Ring Material
- Lap Ring Size
- Lap Ring Type

*Input variables*

- Workpiece Material and its Hardness

- Abrasive Type
- Workpiece Size (diameter)
- Shape of Workpiece
- Type of Workpiece

4) Process control sub-module: This module is intended to provide a combination of recommended pressure, speed of rotation, and time. The following are potential input and output variables:




~ Desired Surface Roughness (μm) +
Initial Surface Roughness (μm) +
Desired Surface Flatness (light-bands) +
Initial Surface Flatness (light-bands) +
MRR ($in^3$/min) +
A Productivity Factor

The following Figure 35 illustrates a simplified framework of the flat-lapping advisory system.

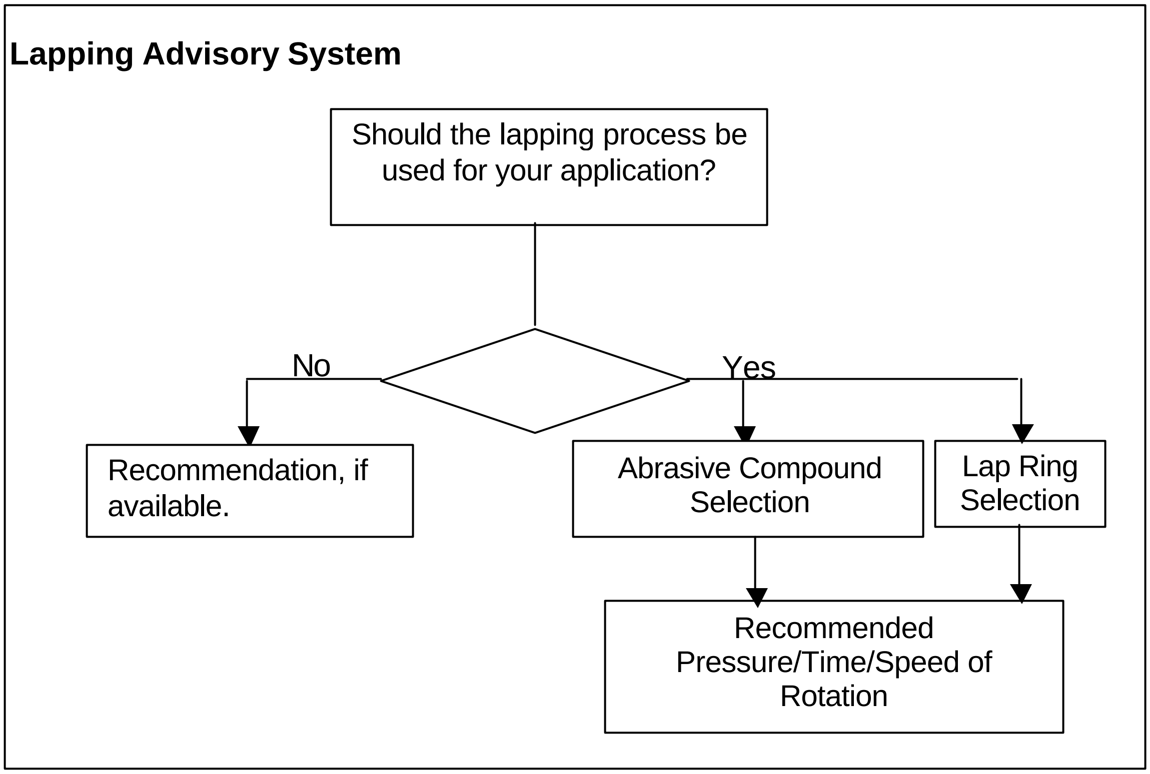



Figure 35 A Tentative Frame Work for the Knowledge Base Subsystem

## 7.2 Knowledge Acquisition

The acquisition of lapping knowledge was completed using four primary approaches.

- The first approach is acquiring lapping detail through an ongoing literature review.
- The second approach is through the interviewing experts in the lapping industry.

- The third approach is through on-site observations (visiting some local lapping facilities).
- The fourth approach is acquiring the data from a series of well-designed experiments conducted at user organizations.

The knowledge acquired are the practiced details and rules-of-thumb in flat-lapping process along with the problems occurring in the process for both manual and mechanical lapping. The results from experiments reveal the relationships among potential parameters and play an important role in this research effort.

### 7.3 Development of System Protocol

A preliminary advisory system for flat lapping was developed using the findings from pilot studies, and information from literature search, as well as experts to form knowledge based. The developed protocol includes:

1) A proposed lapping advisory system architecture
2) A framework for knowledge base
3) Examples of modules and sub-modules including IF-THEN rules

This proposed protocol is intended to be used as a guideline for a more complete lapping advisory system development.

Due to limitations, the pilot studies were focused on a particular abrasive and workpiece material. The following Figure 36 shows a generic framework and scope of developed knowledge based systems. This framework, however, clearly illustrates the direction for further effort to study a more complete set of abrasive types and workpiece materials.

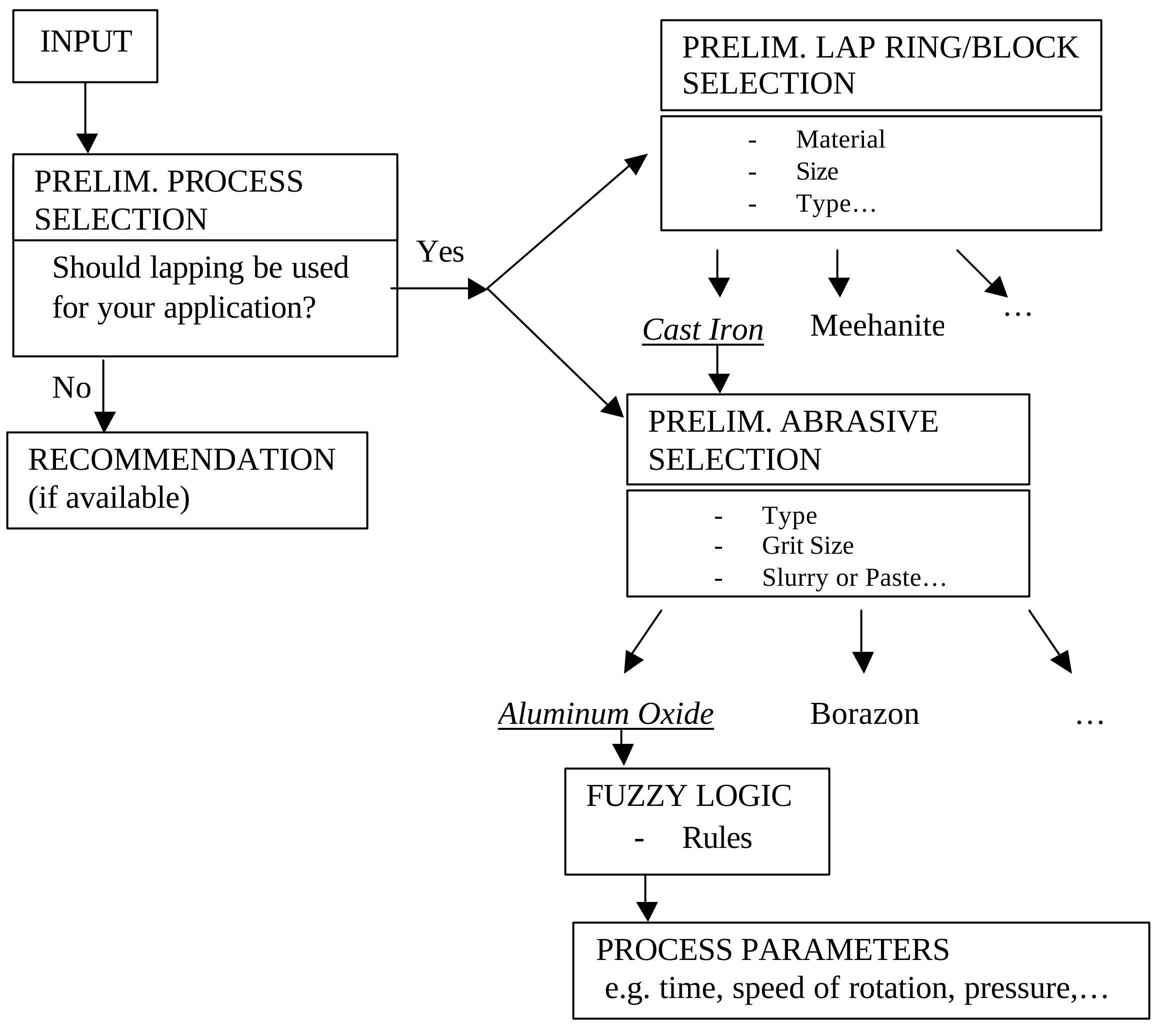



Figure 36 A Generic Framework for the Developed Knowledge Based Subsystem

## 7.4 Knowledge Representation Techniques

Knowledge representation is one of key elements of an advisory system. Rules are one form of knowledge representation that are a formalism for exploring and expressing the knowledge, so as to enable computers to perform as expert consultants and to facilitate the novice operators. As mentioned earlier, rule-based expert systems have shown themselves to be a powerful framework for building knowledge systems. In a rule-based expert system, domain knowledge is translated into a set of rules and stored in the knowledge base. However, in reality, the available information on any problem is almost always imprecise, incomplete and ill-defined; linguistic variables need to be defined as fuzzy variables which are mapped into appropriate numerical domains. This is the case for lapping, in which, the domain knowledge obtained from lapping engineers and/or literature review is often pervaded by imprecision and uncertainty, and the available data are frequently imprecise and incomplete. Hence, the rules in the resultant rule base are often "fuzzy" in nature.

In such a situation, a conventional advisory system technique is usually incapable of solving problems. Consequently, a fuzzy rule-based advisory system becomes attractive in problem solving. Fuzzy set theory has provided us with a unified and effective framework for dealing with the "fuzzy" information. For this research, building an advisory system, extracting knowledge from lapping experts (and/or sources of expertise) and transferring the extracted knowledge to a computer program involves mapping the key concepts, sub-problems and information flow characteristics isolated during conceptualization into formal representation, i.e. creating a rule base.

*Fuzzy Rule-based systems*: By definition, a rule-based advisory system is a computer program that processes problem-specific information contained in the working memory with a set of rules contained in the knowledge base, using an inference engine to infer new information. Rules provide a formal way of representing recommendations, directives, or strategies. In this proposed research, the acquired knowledge of lapping process along with the accurate logic from the parametric (qualitative) models will be expressed as IF-THEN statements; i.e. IF premise (antecedent) THEN prediction (consequent). The variables in premise and antecedent will be represented by fuzzy linguistic variables. The antecedent part of a rule consists of all influential factors of the flat lapping process. The consequent part of a rule is a fuzzy set consisting of a number of predictions associated with different membership grades. These rules will contain in the knowledge base and represent the knowledge in the long-term memory. The incoming input will maintain in the working memory and represent the situations in the short-term memory. These rules are used in reasoning by the fuzzy inference engine in comparing the facts with the antecedents or premises of the rules to see which ones can fire. The following is an example of fuzzy rule used in the system:

<u>Example of Rule</u> (retrieved from Abrasive Selection Sub-module):

IF postRa_is_spFinsh .AND. preRa-is_spFinish .AND. pstFlt_is_vrFlat .AND. preFlt_is_vrFlat .AND. MRR_is_xLow .THEN. Abrasive_is_custolon .AND. grit1_is_1000

The above rule can be interpreted as following:

IF the value of part surface roughness after lapping (postRa) is within the range classified as super finish (spFinish) and IF the value of part surface roughness before lapping (preRa) is within the range classified as super finish and IF the value of surface flatness after lapping (pstFlt) is within the range classified as very flat and IF the value of surface flatness before lapping (preFlt) is within the range classified as very flat and IF the desired material removal rate (MRR) is within the range classified as extremely low, THEN the suggested abrasive type is Custolon with grit size # 1000.

The similar sets of rules were generated for each sub-module and were stored as knowledge base for the advisory system.

## 7.5 Advisory System Development Shell Selection

An advisory system development shell was selected based mainly on data available and practical constraints such as availability and cost. However, the following factors are also considered: 1. the method of knowledge representation, 2. the developer interface, 3. the user interface, 4. the interface with other programs and data files, and 5. the shell vendor's stability and commitment in evaluating shells. The following software packages were under consideration at the early stage of this research:

**1. FuzzyCLIPS** which is a PC-based expert system shell, developed by the National Research Council of Canada , can be used in developing the proposed advisory system. FuzzyCLIPS (an enhanced version of CLIPS) is a C language-based software. The basic elements of FuzzyCLIPS are a fact list that forms a global memory for data, a knowledge base that contains all the rules and initial conditions, an inference engine that controls execution and decides the rules to be executed based on the available facts, and external software. FuzzyCLIPS contains the capability of handling fuzzy concepts and reasoning. It allows any mix of fuzzy and normal terms, numeric-comparison logic controls, and uncertainties in the rule and facts. In this research, the reasoning algorithm which is used in the inference engine may be written in C language.

**2. FIDE** (Fuzzy Inference Development Environment) is a complete environment for the development of fuzzy logic-based system. It exploits the non-linear nature of fuzzy logic by including three debugging and analysis capabilities which target the application. FIDE supports C code by generating ANSI C code for a fuzzy inference unit.

**3. TILShell** is a Windows-based software development tool that provides users with a way to design, debug, and test fuzzy logic expert systems. It provides real-time on-line debugging and tuning of rules, membership functions and rule weights, including addition and deletion of rules.

After a comprehensive consideration of the factors stated above, TILShell was selected and used as development software for this research. Noted here that some modules, e.g. abrasive selection, contains crisp outputs and can be developed using crisp inference engine along with fuzzy variables. In this research, computer programming using Microsoft Visual Basic® was used in developing such module.

## 7.6 Verification and Validation

Advisory systems must be verified and validated before being deployed to prevent the occurrence of disappointing results. Verification involves the determination of whether or not the system is functioning as intended. This may involve program debugging, error analysis, input acceptance, output generation, rationality of operation, run time control, and scope of problem. The knowledge base component of the expert system is the area that requires the most thorough evaluation since it contains the problem-solving strategies of the expert system. Factors of interest in this validation include: completeness, efficiency, validity, maintainability, consistency, precision, soundness, usability, justification, reliability, accommodating, clarity, and quality.

In this research, however, only findings, intuitive models, and a protocol for lapping advisory are proposed. Since the process of verification and validation discussed above only applies to a complete advisory system, the thorough analysis of all the findings from pilot studies serves as verification and validation for the result explanation and protocol. However, the preliminary advisory system was validated by randomly selecting sample cases and, then, comparing the system outputs with responses provided by experts.

# 8.0 A PRELIMINARY FUZZY LOGIC ADVISORY SYSTEM FOR FLAT-SURFACE LAPPING

At the beginning of this research, one of the objectives was to present an advisory system for flat surface lapping. However, the information obtained from the results and findings from the experiments was limited as discussed in the previous Chapter 6. More extensive research is required in order to develop a complete advisory system including the process control module as previously proposed. Thus, instead of developing a complete advisory system, the first two modules were developed as preliminary framework for the proposed advisory system. In this section, the development process of the first two modules (process and abrasive selection modules) is discussed.

## 8.1 Module I – Process Selection

This module is intended to provide users a rough idea of the lapping capabilities. In addition, it is intended to be used as a check-up module for the scope of application covered in the module-II. Once users input all desired outcomes into the expert system, it will provide a general determination (using a fuzzy inference technique) on whether lapping is suitably applicable for the desired set of outcomes based on the capabilities of the process. The system also provides a scaled score (on a scale of 1 to 10) representing the suitability of the application to apply lapping operation using a fuzzy inference technique.

Lapping is a process of finishing using multipoint or random cutting edges. Basically, the lapping process uses a large number of multipoint or random cutting edges for effective removal of material at smaller chip sizes than in the finishing methods that use cutting tools with defined edges. Machining at small chip sizes allows improved finish, closer tolerances, more localized control, and generation of more intricate surface features. Each abrasive finishing process can be distinguished by its capability in terms of cutting speed, material removal rate (MRR), tolerance, and finish as shown the following Table 36 (adapted from Mckee[(4)]).

Table 36 Characteristics of Abrasive Finishing Processes

| **Finishing Processes** | **Cutting Speed (sfm)** | **MRR ($in.^3$/in./min)** | **Tolerance (μin.)** | **Finish (μin.)** |
|---|---|---|---|---|
| **Rough grinding** | | | | |
| With grinding wheels | 12,000-20,000 | 30-100 | ±0.250-1.0<br>±0.100 | 100-1000 |
| Belt grinding | 3,000-5,000 | 0.6-30 | ±0.005 | 100-1000 |
| **Precision grinding** | | | | |
| With grinding wheels | | | | |
| Present | 6000-16000 | 0.01-5 | ±0.0001-0.005 | 0-50 |
| Future | | | | |
| Belt grinding | 3000-7500 | ≤50 | ±10μin. | 0.1 |
| **High-precision abrasive finishing** | | | | |
| Honing | 50-200 | 0.0075 | 20-50μin. | 10-20 |
| ***Lapping*** | ***<50*** | ***< 0.0005*** | ***<20μin.*** | ***1-4*** |
| Polishing | Very Slow | NA | | |

Thus, to indicate whether lapping is capable for a particular set of outcomes, the following tentative model representing potential parameters can be used.

Decision ~ MRR($in^3$/in/min) + Desired Tolerance ($\mu$inch)

+ Desired Surface Flatness (lightbands)

+ Desired Surface Roughness ($\mu$m)

The above potential parameters are represented by fuzzy variables along with their membership functions. In developing this preliminary advisory system, membership functions were assigned by intuition. Intuition involves contextual and semantic knowledge about an issue; it can also involve linguistic truth values about this knowledge.[(90)] Most of membership functions used in this preliminary system are normal and convex. A normal fuzzy set is one whose membership function has at least one element x in the universe whose membership value is unity. A convex fuzzy set is described by a membership function whose membership values are monotonically increase, or decrease, or whose membership values are strictly monotonically increasing then strictly monotonically decreasing with increasing values of elements in the universe set.[(77)] There are two types of fuzzy variables in the context of the ongoing discussion in this chapter: Input Variables and Action Variables (also called output variables).

*Input Variables*

1. Material Removal Rate (MRR)

Full Scale 0-0.001 $in^3$/in/min

For lapping process, MRR is generally not greater than 0.0005 $in^3$/in/min.

Table 37 Membership Functions and Fuzzy Numbers of Fuzzy Variable *MRR*

| Membership Functions | Shape | Fuzzy Number |
|---|---|---|
| xLow | Trapezoidal | (0 0 0.0005 0.00075) |
| Low | Trapezoidal | (0.0005 0.00075 0.001 0.001) |

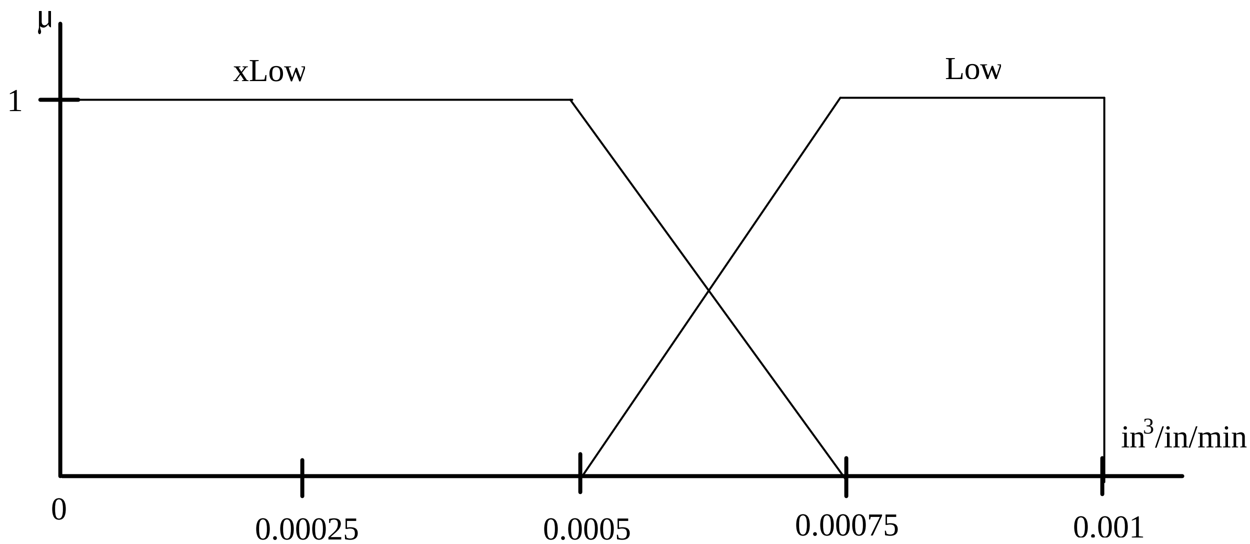



Figure 37 Membership Functions of Fuzzy Variable *MRR*

Figure 37 shows trapezoidal membership functions of *xLow* and *Low* fuzzy sets. The values of *MRR* between 0 and 0.0005 $in^3$/in/min are considered members of *xLow* fuzzy set with 1.0 (probability) degree of membership and not a member of *Low* fuzzy set (0 degree of membership). The values of *MRR* between 0.0005 and 0.00075 $in^3$/in/min are considered members of both *xLow* and *Low* fuzzy sets with degree of membership ranging from 1.0 to 0. The values of *MRR* between 0.00075 and 0.001 $in^3$/in/min are considered members of *Low* fuzzy set with 1.0 (probability) degree of membership and not a member of x*Low* fuzzy set (0 degree of membership).

2. Tolerance

Scale 0-40 μin

For the lapping process, tolerance is generally not greater than 20 μin.

Table 38 Membership Functions and Fuzzy Numbers of Fuzzy Variable *Tolerance(Tolerance)*

| Membership Functions | Shape | Fuzzy Number |
|---|---|---|
| xClose | Trapezoidal | (0 0 20 30) |
| close | Trapezoidal | (20 35 40 40) |

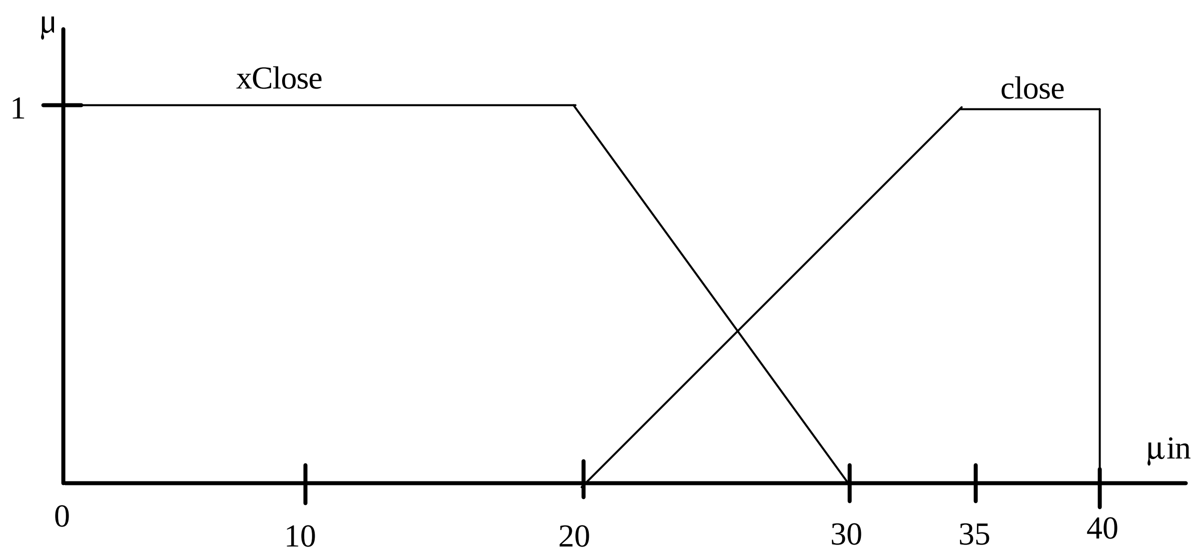



Figure 38 Membership Functions of Fuzzy Variable *Tolerance*

Figure 38 shows trapezoidal membership functions of *xClose* and *Close* fuzzy sets. The values of *Tolerance* between 0 and 20 μin are considered members of *xClose* fuzzy set with 1.0 (probability) degree of membership and not a member of *Close* fuzzy set (0 degree of membership). The values of *Tolerance* between 20 and 30 μin are considered members of both *xClose* and *Close* fuzzy sets with degree of membership ranging from 1.0 to 0. The values of *Tolerance* between 30 and 40 μin are considered members of *Close* fuzzy set with 1.0 (probability) degree of membership and not a member of *xClose* fuzzy set (0 degree of membership).

3. Desired Surface Flatness (Des_Flatness)

Scale 1-10 lightbands

For lapping process, flatness is generally within 1-4 lightbands.

Table 39 Membership Functions and Fuzzy Numbers of Fuzzy Variable *Desired Surface Flatness (Des_Flatness)*

| Membership Functions | Shape | Fuzzy Number |
|---|---|---|
| xFlat | Trapezoidal | (1 1 4 6) |
| Flat | Trapezoidal | (4 6.25 10 10) |

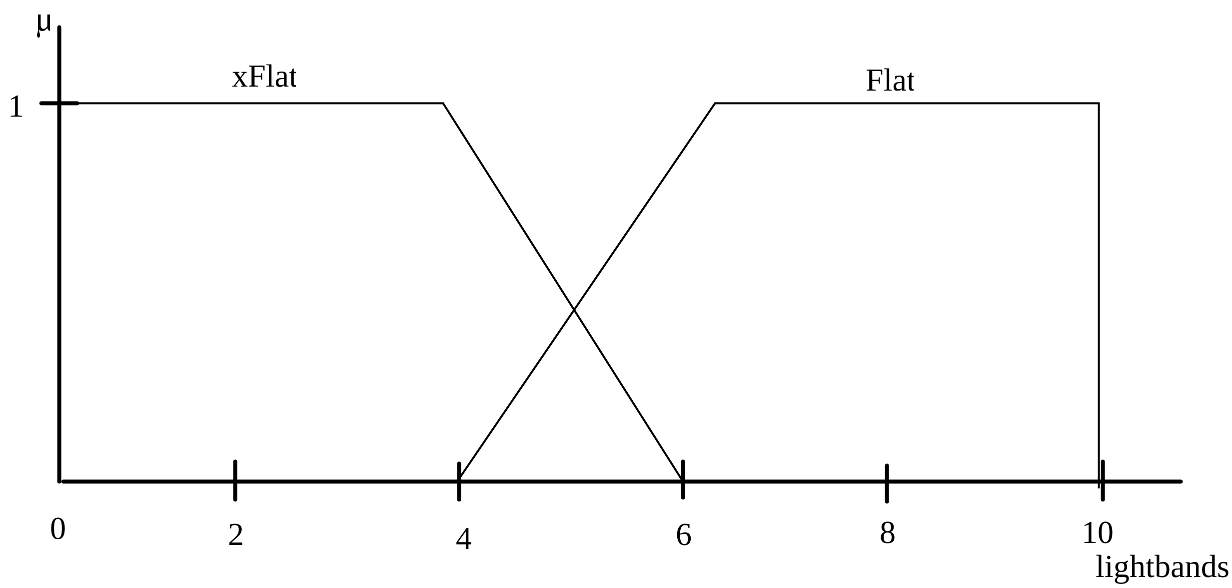



Figure 39 Membership Functions of Fuzzy Variables *(Des_Flatness)*

Figure 39 shows trapezoidal membership functions of *xFlat* and *Flat* fuzzy sets. The values of *Desired Surface Flatness* between 0 and 4 lightbands are considered members of *xFlat* fuzzy set with 1.0 (probability) degree of membership and not a member of *Flat* fuzzy set (0 degree of membership). The values of *Desired Surface Flatness* between 4 and 6 lightbands are considered members of both *xFlat* and *Flat* fuzzy sets with degree of membership ranging from 1.0 to 0. The values of *Desired Surface Flatness* between 6 and 10 lightbands are considered members of *Flat* fuzzy set with 1.0 (probability) degree of membership and not a member of *xFlat* fuzzy set (0 degree of membership).

4. Desired Surface Roughness (Des_Rough)

Scale 0-32 µin

For lapping process, roughness is generally within 1-13 µin.

Table 40 Membership Functions and Fuzzy Numbers of Fuzzy Variable *Desired Surface Roughness (Des_rough)*

| Membership Functions | Shape | Fuzzy Number |
|---|---|---|
| SPFinish | Trapezoidal | (0 0 13 20) |
| Finish | Trapezoidal | (13 20 32 32) |

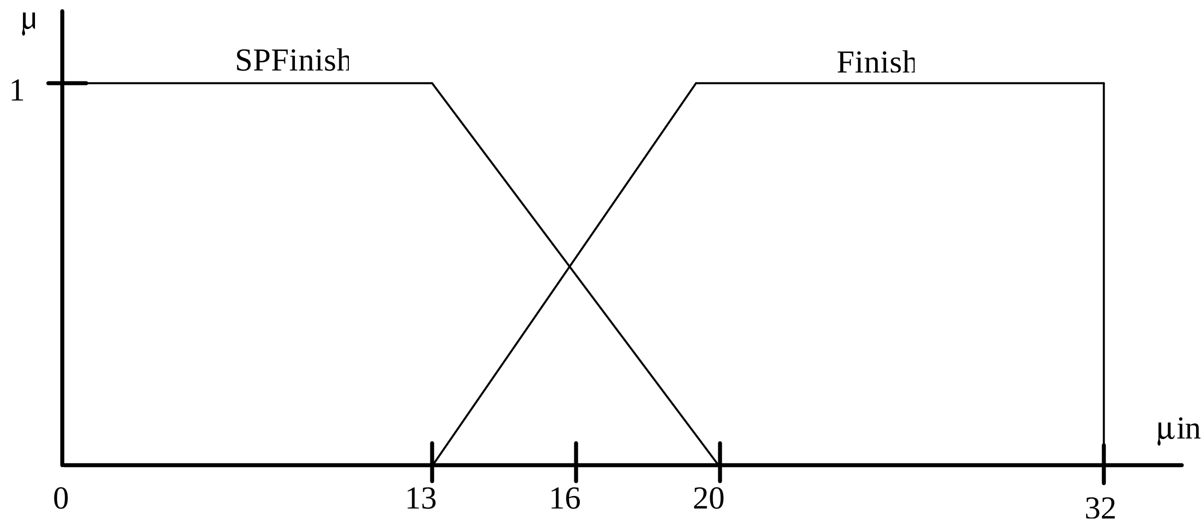



Figure 40 Membership Functions of Fuzzy Variable *Desired Surface Roughness (Des_Rough)*

Figure 40 shows trapezoidal membership functions of *SPFinish* and *Finish* fuzzy sets. The values of *Desired Surface Roughness* between 0 and 13 μin are considered members of *SPFinish* fuzzy set with 1.0 (probability) degree of membership and not a member of *Finish* fuzzy set (0 degree of membership). The values of *Desired Surface Roughness* between 13 and 20 μin are considered members of both *SPFinish* and *Finish* fuzzy sets with degree of membership ranging from 1.0 to 0. The values of *Desired Surface Roughness* between 20 and 32 μin are considered members of *Finish* fuzzy set with 1.0 (probability) degree of membership and not a member of *SPFinish* fuzzy set (0 degree of membership).

*Output Variable*

Process

Scale: score from 0 to 10.

Table 41 Membership Functions and Fuzzy Numbers of Fuzzy Variable *Process*

| Membership Functions | Shape | Fuzzy Number |
|---|---|---|
| Lapping | Trapezoidal | (0 0 3 7.5) |
| Others | Trapezoidal | (3 7.5 10 10) |

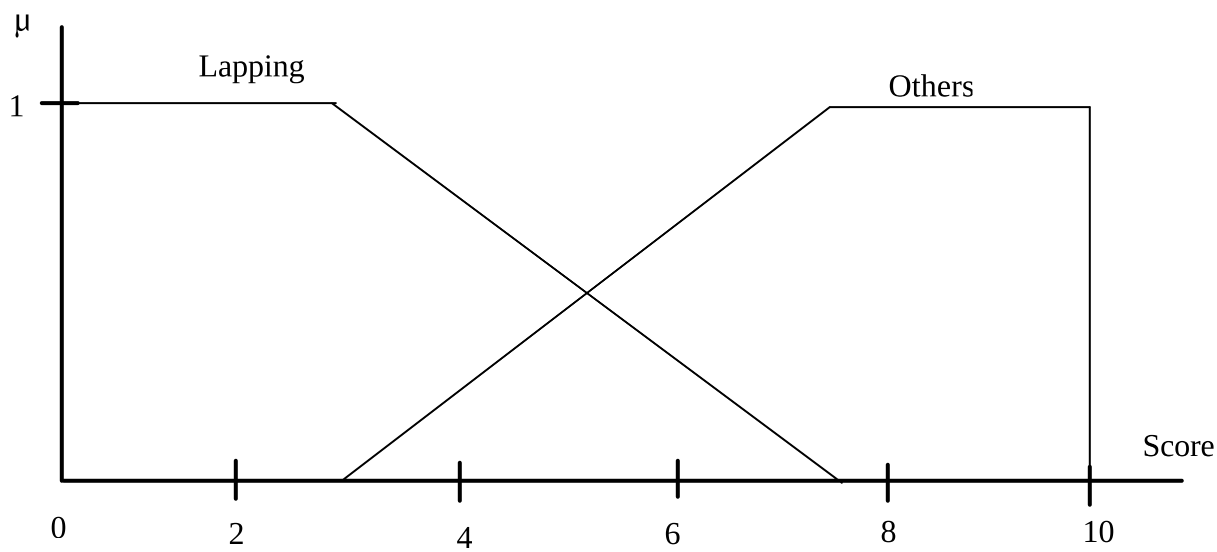



Figure 41 Membership Functions of Fuzzy Variable *Process*

Figure 41 shows trapezoidal membership functions of *Lapping* and *Others* fuzzy sets. The values of *Process* between 0 and 3 are considered members of *Lapping* fuzzy set with 1.0 (probability) degree of membership and not a member of *Others* fuzzy set (0 degree of membership). The values of *Process* between 3 and 7.5 are considered members of both *Lapping* and *Others* fuzzy sets with degree of membership ranging from 1.0 to 0. The values of *Process* between 7.5 and 10 are considered members of *Others* fuzzy set with 1.0 (probability) degree of membership and not a member of *Lapping* fuzzy set (0 degree of membership).

The fuzzy variables and membership functions explained in this section were used in developing rules for module-I. Details of variable nomenclature, rules, and an example of screen for module-I are shown in Appendix C.

## 8.2 Module II – Abrasive Compound Selection

This module is intended to provide users a suggestion of what kind of abrasive should be used for a particular application. Once users enter all required inputs into the advisory system, it will provide a recommendation of abrasive type and grit size(s) for the particular set of inputs. Noted here that this module utilizes the concepts of fuzzy numbers and membership functions, however, the general rule-based approach is used as inference engine because the outputs are crisp (Abrasive Type and Grit Size).

Abrasive materials provide the cutting edges in abrasive finishing processes, so they are an essential element of any abrasive product. The selection of the abrasive is influenced primarily by the material of the workpiece and its hardness, the total amount of stock removal, and the final finish required on the work. Hardness indicates the kind of abrasive, as the hardness of the abrasive must equal that of the work. In general, the greater the area to be lapped, the coarser the grain may be. These considerations, however, must be weighed in relation to the finish required on the workpiece. Fine finishes require a fine grain. Yet, if surface finish is not critical, a coarser grain can be specified, with a not very fine finish as a result. Thus, to select type and grit size(s) of abrasive for a particular set of inputs, the following tentative model representing potential parameters can be used.

Type of Abrasive + Grit Size ~ Type of workpiece material (Rockwell C) +
Desired Surface Roughness ($\mu$m) +
Initial Surface Roughness ($\mu$m) +
Desired Surface Flatness (lightbands) +
Initial Surface Flatness (lightbands) +
MRR ($in^3$/in/min)

The above potential parameters are represented by fuzzy variables along with their membership functions. Again, in developing this preliminary advisory system, membership functions were assigned by intuition. Most of membership functions used in this preliminary system are normal and convex. As in the first module, there are two types of fuzzy variables: Input Variables and Action Variables (also called output variables).

*Input Variables*

1. *Type of workpiece material (Crisp)*

   - Metal, Carbon, Stainless, Brass, Bronze, Hard Face (materials that have been through the process of surface hardening). These materials are most widely used for valve and nozzle seats.

2. *Desired Surface Roughness (postRa)* - Scale (Ra) 0 - 0.5 μm

Table 42 Membership Functions and Fuzzy Numbers of Fuzzy Variable *Desired Surface Roughness (postRa)*

| Membership Functions | Shape | Fuzzy Number |
|---|---|---|
| SPFinish | Trapezoidal | (0 0 0.1 0.2) |
| HiFinish | Triangle | (0.1 0.2 0.4) |
| NrFinish | Triangle | (0.2 0.4 0.5) |

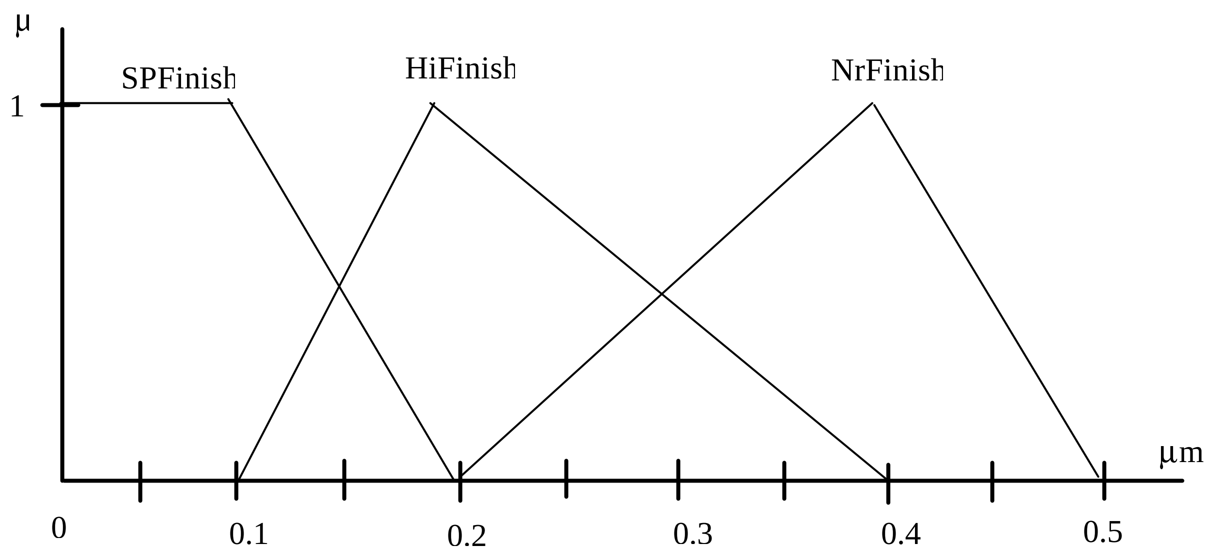



Figure 42 Membership Functions of Fuzzy Variables *Desired Surface Roughness (postRa)*

Figure 42 shows trapezoidal and triangle membership functions of *SPFinish*, *HiFinish*, and *NrFinish* fuzzy sets. The values of *Desired Surface Roughness* between 0 and 0.1 μm are considered members of *SPFinish* fuzzy set with 1.0 (probability) degree of membership and not a member of *HiFinish* and *NrFinish* fuzzy sets (0 degree of membership). The values of *Desired Surface Roughness* between 0.1 and 0.2 μm are considered members of both *SPFinish* and *HiFinish* fuzzy sets with degree of membership ranging from 1.0 to 0. The values of *Desired Surface Roughness* between 0.2 and 0.4 μm are considered members of both *HiFinish* and *NrFinish* fuzzy sets with a degree of membership ranging from 1.0 to 0, but not a member of *SPFinish* fuzzy set (0 degree of membership). The values of *Desired Surface Roughness* between 0.4 and 0.5 μm are considered members of *NrFinish* fuzzy set with more than 0 (probability) degree of membership and not a member of *SPFinish* and *HiFinish* fuzzy set (0 degree of membership).

3. *Initial Surface Roughness (preRa)* - Scale (Ra) 0-1.0 μm

Table 43 Membership Functions and Fuzzy Numbers of Fuzzy Variable *Initial Surface Roughness (preRa)*

| Membership Functions | Shape | Fuzzy Number |
|---|---|---|
| SPFinish | Trapezoidal | (0 0 0.1 0.2) |
| HiFinish | Triangle | (0.1 0.2 0.4) |
| NrFinish | Triangle | (0.2 0.4 0.8) |
| RoFinish | Triangle | (0.4 0.8 1.0) |

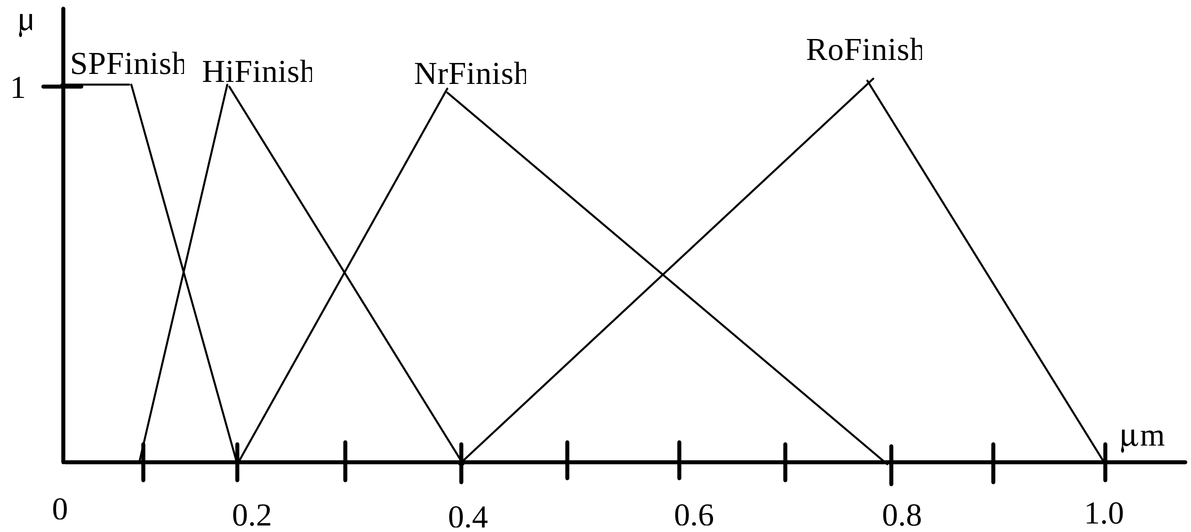



Figure 43 Membership Functions of Fuzzy Variable *Initial Surface Roughness (preRa)*

Figure 43 shows trapezoidal and triangle membership functions of *SPFinish*, *HiFinish*, *NrFinish*, and *RoFinish* fuzzy sets. The values of *Initial Surface Roughness* between 0 and 0.1 μm are considered members of *SPFinish* fuzzy set with 1.0 (probability) degree of membership and not a member of *HiFinish*, *NrFinish*, and *RoFinish* fuzzy sets (0 degree of membership). The values of *Initial Surface Roughness* between 0.1 and 0.2 μm are considered members of both *SPFinish* and *HiFinish* fuzzy sets with degree of membership ranging from 1.0 to 0, but not a member of *NrFinish* and *RoFinish* fuzzy sets (0 degree of membership). The values of *Initial Surface Roughness* between 0.2 and 0.4 μm are considered members of both *HiFinish* and *NrFinish* fuzzy sets with a degree of membership ranging from 1.0 to 0, but not a member of *SPFinish* and *RoFinish* fuzzy sets (0 degree of membership). The values of *Initial Surface Roughness* between 0.4 and 0.8 μm are considered members of both *NrFinish* and

*RoFinish* fuzzy sets with a degree of membership ranging from 1.0 to 0, but not a member of *SPFinish* and *HiFinish* fuzzy sets (0 degree of membership). The values of *Initial Surface Roughness* between 0.8 and 1.0 µm are considered members of *RoFinish* fuzzy set with more than 0 (probability) degree of membership and not a member of *SPFinish*, *HiFinish*, and *NrFinish* fuzzy set (0 degree of membership).

4. *Desired Surface Flatness (pstFlt)* - Scale 1-4 lightbands

Table 44 Membership Functions and Fuzzy Number of Fuzzy Variable *Desired Surface Flatness (pstFlt)*

| Membership Functions | Shape | Fuzzy Number |
|---|---|---|
| xFlat | Trapezoidal | (0 0 1.25 2.75) |
| vrFlat | Trapezoidal | (1.25 2.75 4 4) |

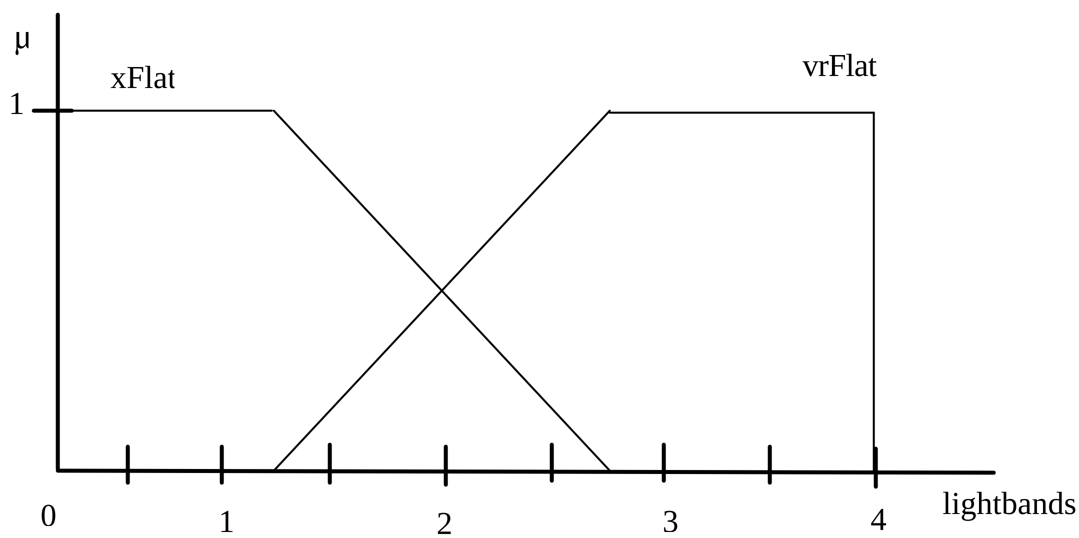



Figure 44 Membership Functions of Fuzzy Variable *Desired Surface Flatness (pstFlt)*

Figure 44 shows trapezoidal membership functions of *xFlat* and *vrFlat* fuzzy sets. The values of *Desired Surface Flatness* between 0 and 1.25 lightbands are considered members of *xFlat* fuzzy set with 1.0 (probability) degree of membership and not a member of *vrFlat* fuzzy set (0 degree of membership). The values of *Desired Surface Flatness* between 1.25 and 2.75 lightbands are considered members of both *xFlat* and *vrFlat* fuzzy sets with degree of membership ranging from 1.0 to 0. The values of *Desired Surface Flatness* between 2.75 and 4 lightbands are considered members of *vrFlat* fuzzy set with 1.0 (probability) degree of membership and not a member of *xFlat* fuzzy set (0 degree of membership).

5. *Initial Surface Flatness (preFlt)* - Scale 0-10 lightbands

Table 45 Membership Functions and Fuzzy Numbers of Fuzzy Variable *Initial Surface Flatness (preFlt)*

| Membership Functions | Shape | Fuzzy Number |
|---|---|---|
| xFlat | Trapezoidal | (0 0 1.6 3.2) |
| vrFlat | Triangle | (1.6 3.2 4.8) |
| mFlat | Triangle | (3.2 4.8 6.4) |

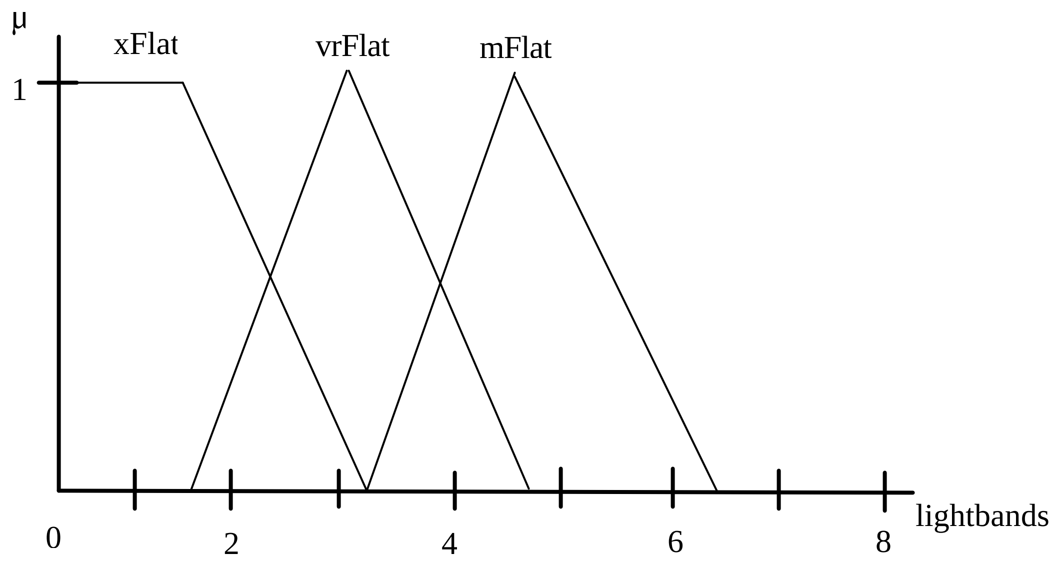



Figure 45 Membership Functions of Fuzzy Variable *Initial Surface Flatness (preFlt)*

Figure 45 shows trapezoidal and triangle membership functions of *xFlat*, *vrFlat,* and *mFlat* fuzzy sets. The values of *Initial Surface Flatness* between 0 and 1.6 lightbands are considered members of *xFlat* fuzzy set with 1.0 (probability) degree of membership and not a member of both *vrFlat* and *mFlat* fuzzy set (0 degree of membership). The values of *Initial Surface Flatness* between 1.6 and 3.2 lightbands are considered members of both *xFlat* and *vrFlat* fuzzy sets with degrees of membership ranging from 1.0 to 0, but not a member of *mFlat* fuzzy set (0 degree of membership). The values of *Initial Surface Flatness* between 3.2 and 4.8 lightbands are considered members of both *vrFlat* and *mFlat* fuzzy sets with degrees of membership ranging from 1.0 to 0, but not a member of *xFlat* fuzzy set (0 degree of membership). The values of *Initial Surface Flatness* between 4.8 and 6.4 lightbands are considered members of *mFlat* fuzzy sets with degrees of membership more than 0, but not a member of *xFlat* and *vrFlat* fuzzy set (0 degree of membership).

6. *Material Removal Rate (MRR)* - Scale 0-0.0005 $in^3$/in/min

Table 46 Membership Functions and Fuzzy Numbers of Fuzzy Variable *Material Removal Rate (MRR)*

| Membership Functions | Shape | Fuzzy Number |
|---|---|---|
| xLow | Trapezoidal | (0 0 0.00016 0.00025) |
| vrLow | Triangle | (0.00016 0.00025 0.00034) |
| Low | Trapezoidal | (0.00025 0.00034 0.0005) |

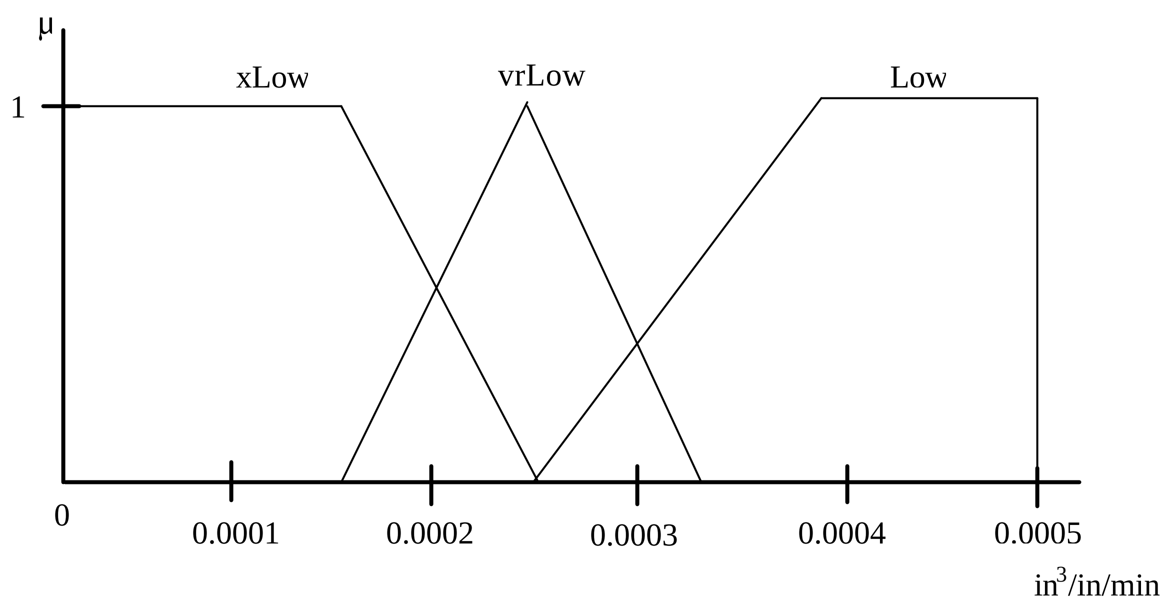



Figure 46 Membership Functions of Fuzzy Variable *Material Removal Rate (MRR)*

Figure 46 shows trapezoidal membership functions of *xLow, vrLow,* and *Low* fuzzy sets. The values of *MRR* between 0 and 0.00016 $in^3$/in/min are considered members of *xLow* fuzzy set with 1.0 (probability) degree of membership and not a member of *vrLow* and *Low* fuzzy set (0 degree of membership). The values of *MRR* between 0.00016 and 0.00025 $in^3$/in/min are considered members of both *xLow* and *vrLow* fuzzy sets with degree of membership ranging from 1.0 to 0, but not a member of

*Low* fuzzy set (0 degree of membership). The values of *MRR* between 0.00025 and 0.00034 $in^3$/in/min are considered members of both *vrLow* and *Low* fuzzy sets with degree of membership ranging from 1.0 to 0, but not a member of x*Low* fuzzy set (0 degree of membership). The values of *MRR* between 0.00034 and 0.0005 $in^3$/in/min are considered members of *Low* fuzzy set with degree of membership more than 0, but not a member of x*Low* and *vrLow* fuzzy sets (0 degree of membership).

*Output Variables*

There are two output variables, Type of Abrasive and Grit Size, in this module. These two variables are treated as crisp variables. Noted here that output Grit Size can be represented in a combination of more than one size, if required.

1. Type of Abrasive

   Diamond, Borazon CBN, Norbide, Boron Carbide, Crystolon, Silicon Carbide, Alundum, Aluminum Oxide, 38 White Aluminum Oxide, Fused Alumina, Corundum, Garnet, Quartz, Unfused Alumina, Linde Powers, Red Rouge (Ferric oxide), Green Rouge (Chromium oxide)

2. Grit sizes

   100, 120, 150, 180, 220, 240, 280, 320, 400, 500, 600, 900, 1000, 1200

The above fuzzy and crisp variables as well as their membership functions were used in developing rules for module-II. Details of variable nomenclature, rules, and examples of module-II screens are shown in Appendix C.

## 8.3 System Validation

The module-II in this preliminary system was validated by comparing the system outputs with responses given by experts for each sample set of inputs. A set of sample cases (30 cases) was randomly selected and presented to two experts. The experts, then, considered each set of input values and provided suggestion on appropriate abrasive types and grit sizes. The responses provided by the experts were, then, compared with system outputs with respect to the selected cases. Some examples of the comparison are shown in the Table 55 (listed in Appendix C). The comparison indicated that 70% of the sample system outputs were exactly the same as responses from experts, on the other hand, 30% of the system outputs were slightly different from experts' responses. However, these differences are only in some grit size numbers, which are, in fact, interchangeable as long as they are within acceptable ranges with respect to the applications of interests. In sum, the module-II in the preliminary system, which utilizes fuzzy linguistic variables and membership function concepts, provides a promising approach in capturing human knowledge.

# 9.0 CONCLUSIONS AND FUTURE WORK

## 9.1 Conclusion

This dissertation has studied critical process parameters of flat surface lapping with specific application to reconditioning valve discs and nozzle seats via a series of statistically designed experiments. The results from data analyses indicate that, in general, *Part Type, Part Diameter,* and *Initial Roughness* have significant effects on *Surface Flatness, Surface Roughness,* and *MRR* in both manual and mechanical lapping. The *Grit Size* of abrasive also plays an important role in case of mechanical lapping. However, the relationships among the critical parameters are complicated and difficult to explain, primarily due to the complex interactions that exist among the critical parameters. Hence, lapping model development is significantly more laborious and time consuming than originally anticipated.

The lapping tool designed as part of this dissertation shows a promising performance in term of improving process consistency and capturing the mechanism of manual lapping for on-site valve repair. The findings from the experiments also indicate that, compared to those for manual lapping, critical process control parameters for mechanical lapping have stronger linear relationships with the process outcomes, mainly due to a larger number of controllable parameters. Thus, with an extensive study and test to better design the lapping tool, the tool can help mechanize and standardize flat lapping operation, especially for on-site valve repair.

A preliminary lapping advisory system with an application of fuzzy logic was also proposed. The system provides promising results with the use of fuzzy logic, especially with the application of linguistic variables because the values of critical lapping parameters are generally quantified as ranges. In addition, as indicated by the results of experiments, the relationships among critical process parameters are complicated, thus fuzzy logic is also an appropriate technique for inference engine. The preliminary advisory system was validated in term of the ability of the system to capture human knowledge by comparing system outputs with answers from experts in the field.

The findings from this dissertation are based on the series of carefully designed experiments and subsequent analyses. Thus, these results are viable and an asset for further study in modeling flat lapping process. The preliminary advisory system can also be used as a protocol or guideline in further developing an extensive system.

## 9.2 Future Work

The followings are proposed directions for future research:

- Extend the scope of experiments in terms of factors and levels, e.g. more variety of lap ring type, material, size, abrasive.
- With a wider scope and more extensive experiments, explore the possibility of integrating Neural Networks to the advisory system instead of building explicit lapping models.
- Examine flat lapping with other types of application to compare the nature of critical process parameters.

- Investigate the micro-level critical effects, e.g. surface properties before and after lapping, in order to explain the interactions among process parameters.
- Implement a more complete advisory system with additional data.

# APPENDIX A

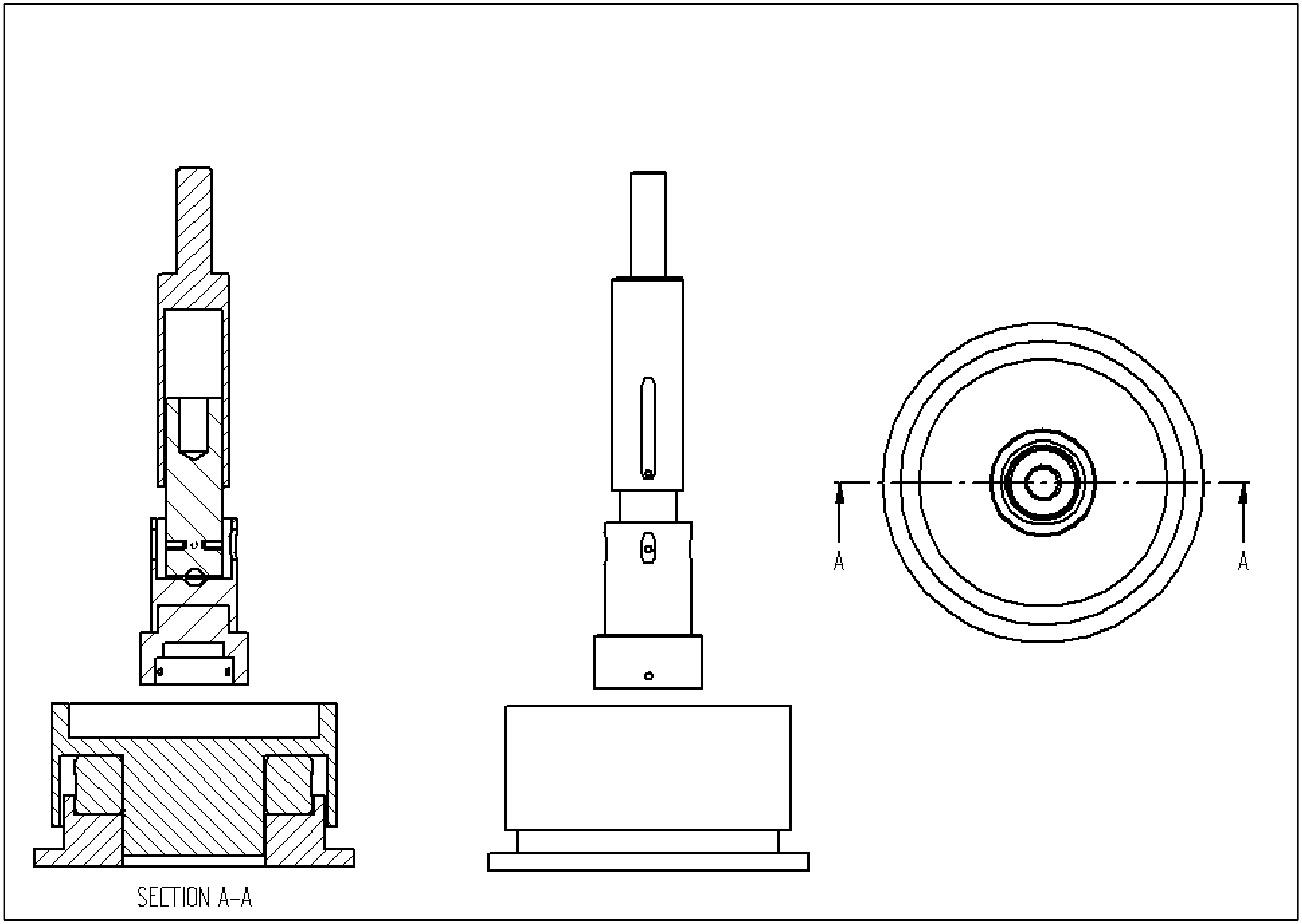



Figure 47 Crossed-Section of Mechanical Lapping Tool

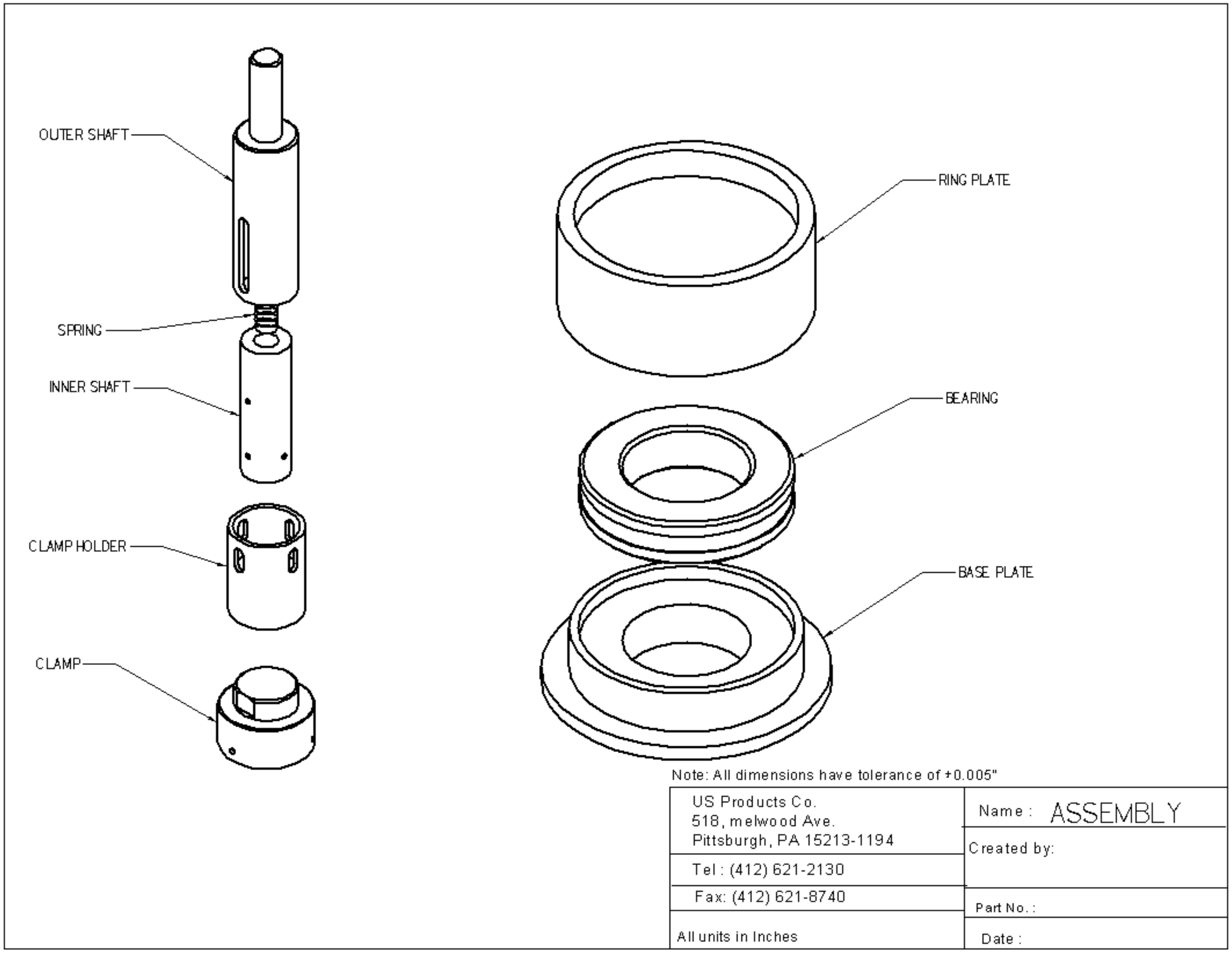



Figure 48 Mechanical Lapping Tool

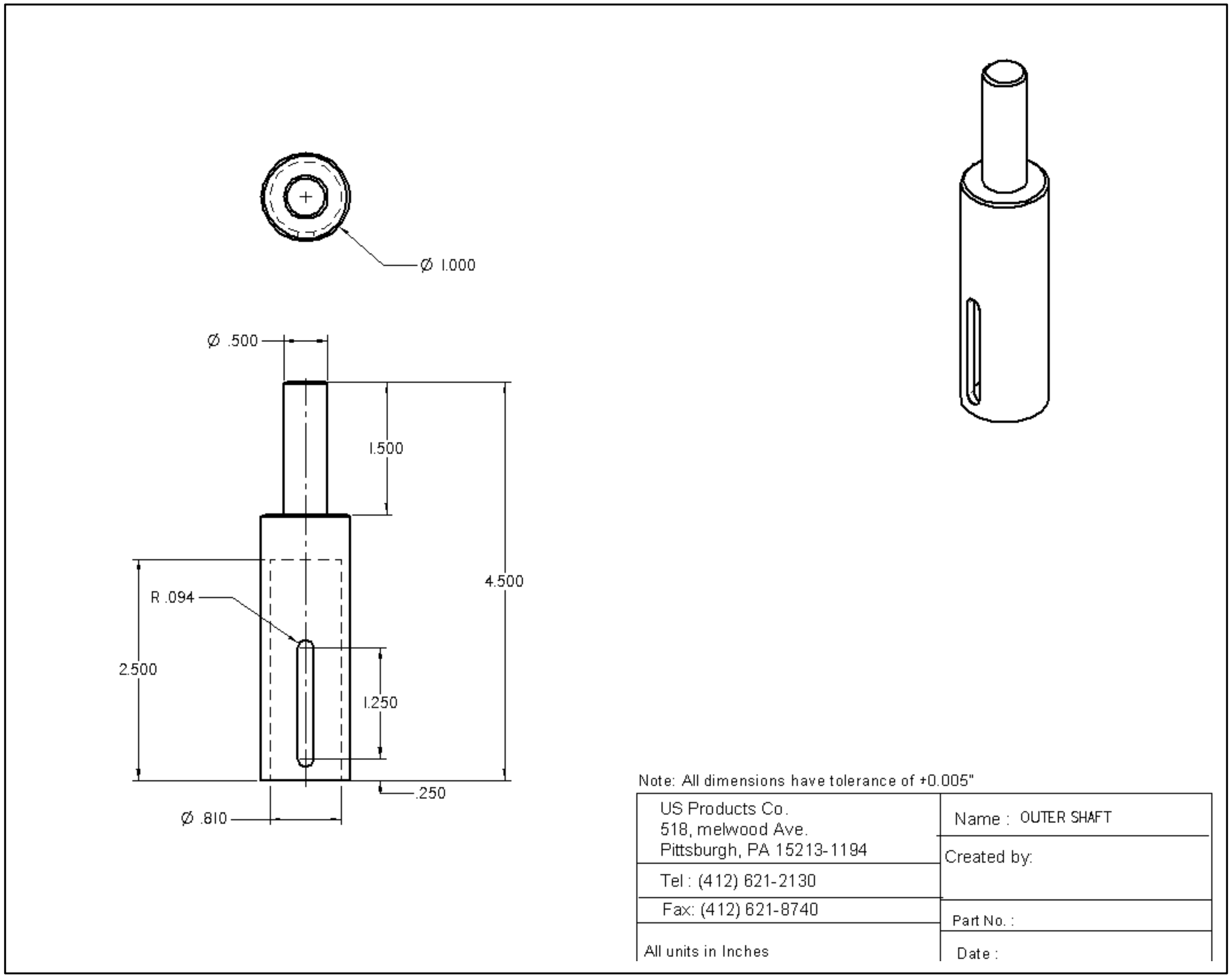



Figure 49 Outer Shaft

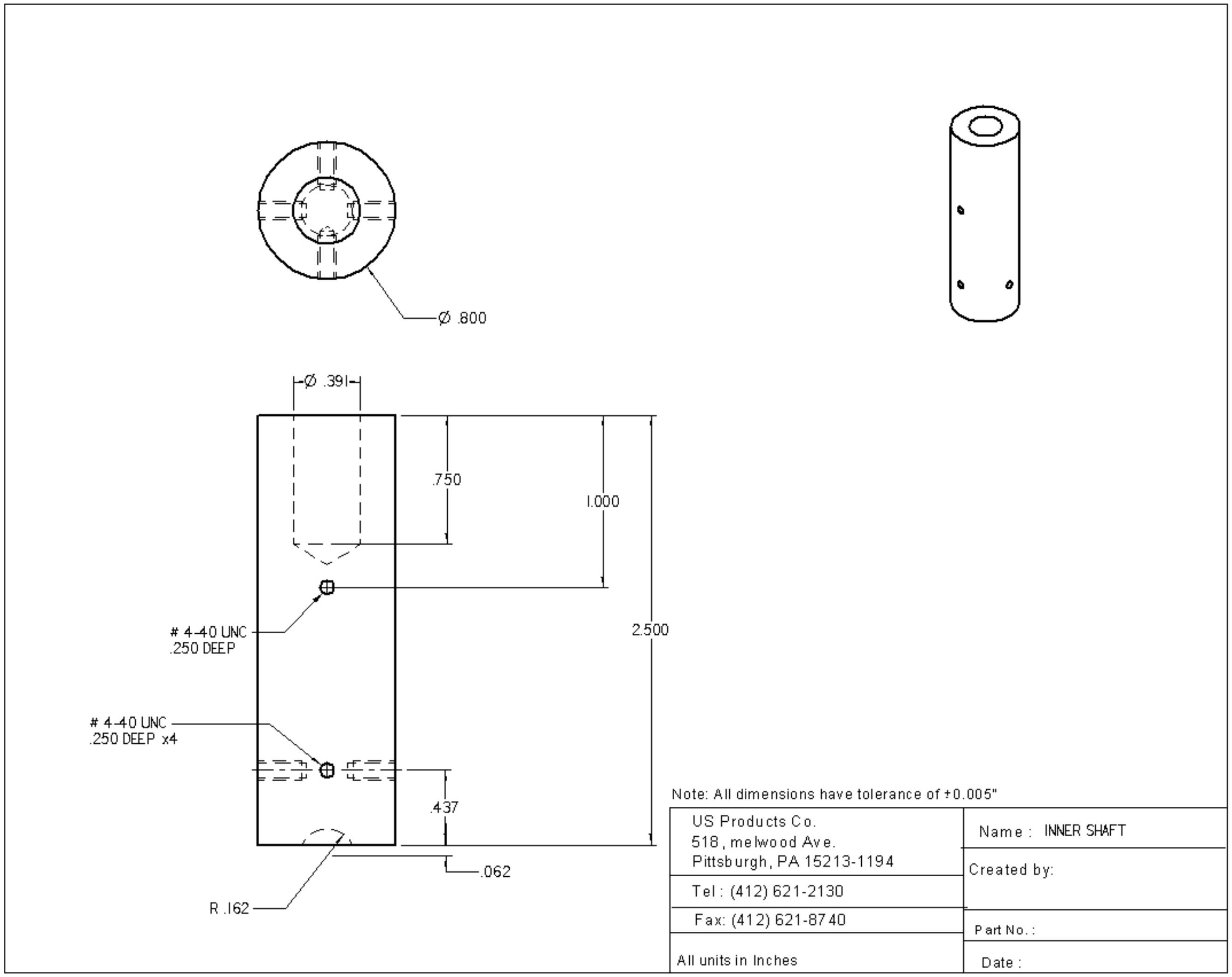



Figure 50 Inner Shaft

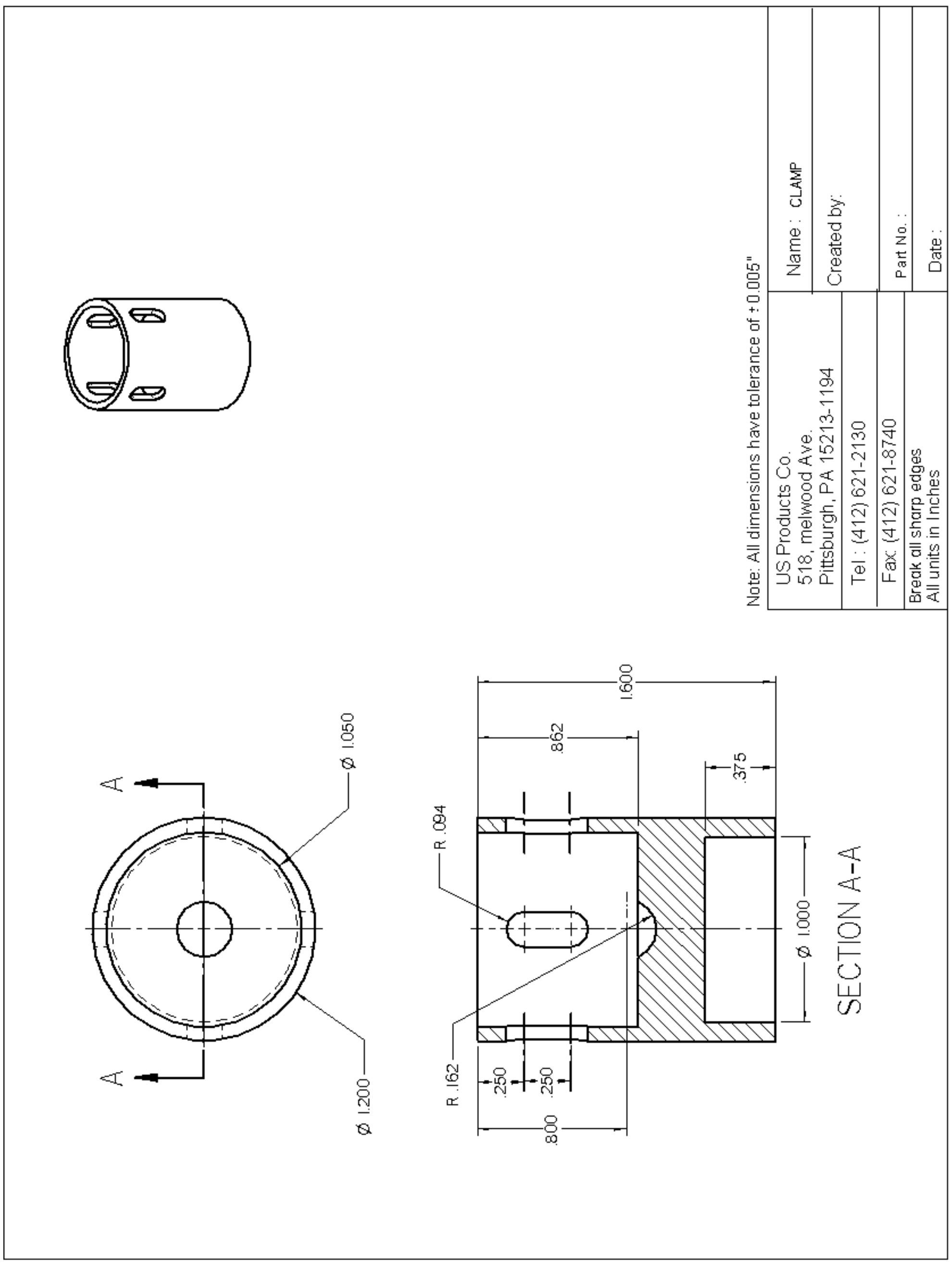



Figure 51 Clamp Holder

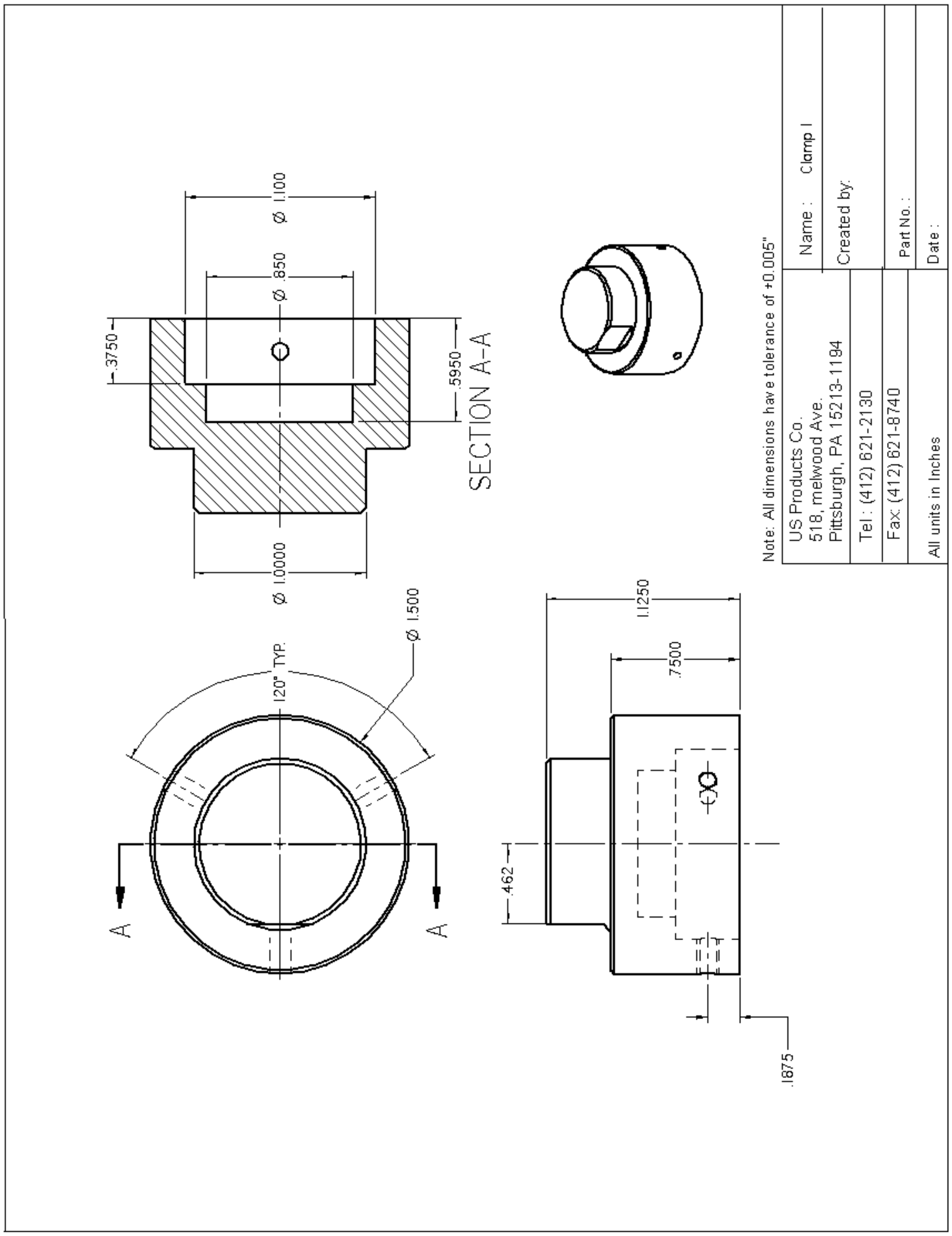



Figure 52 Clamp-I

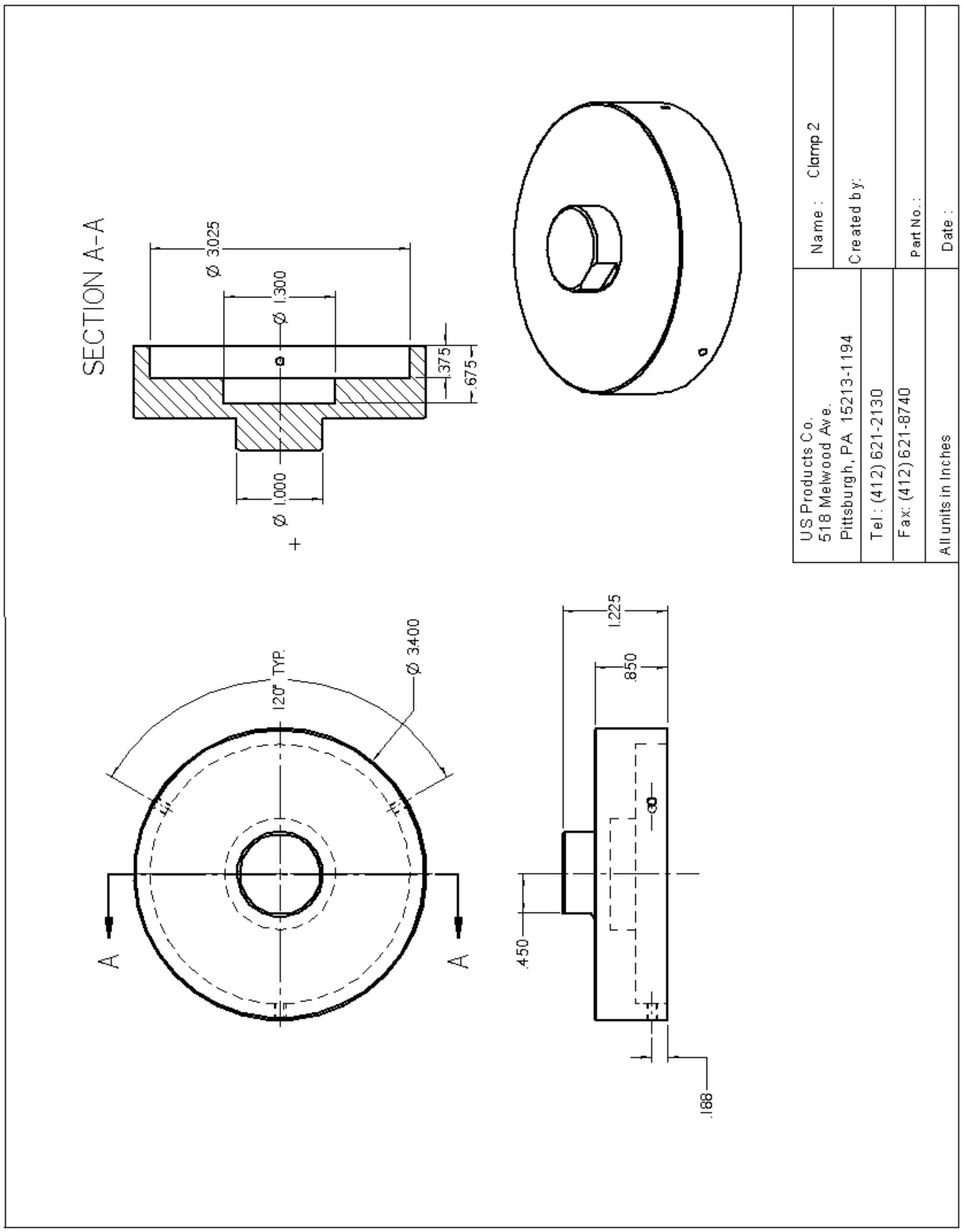



Figure 53 Clamp-II

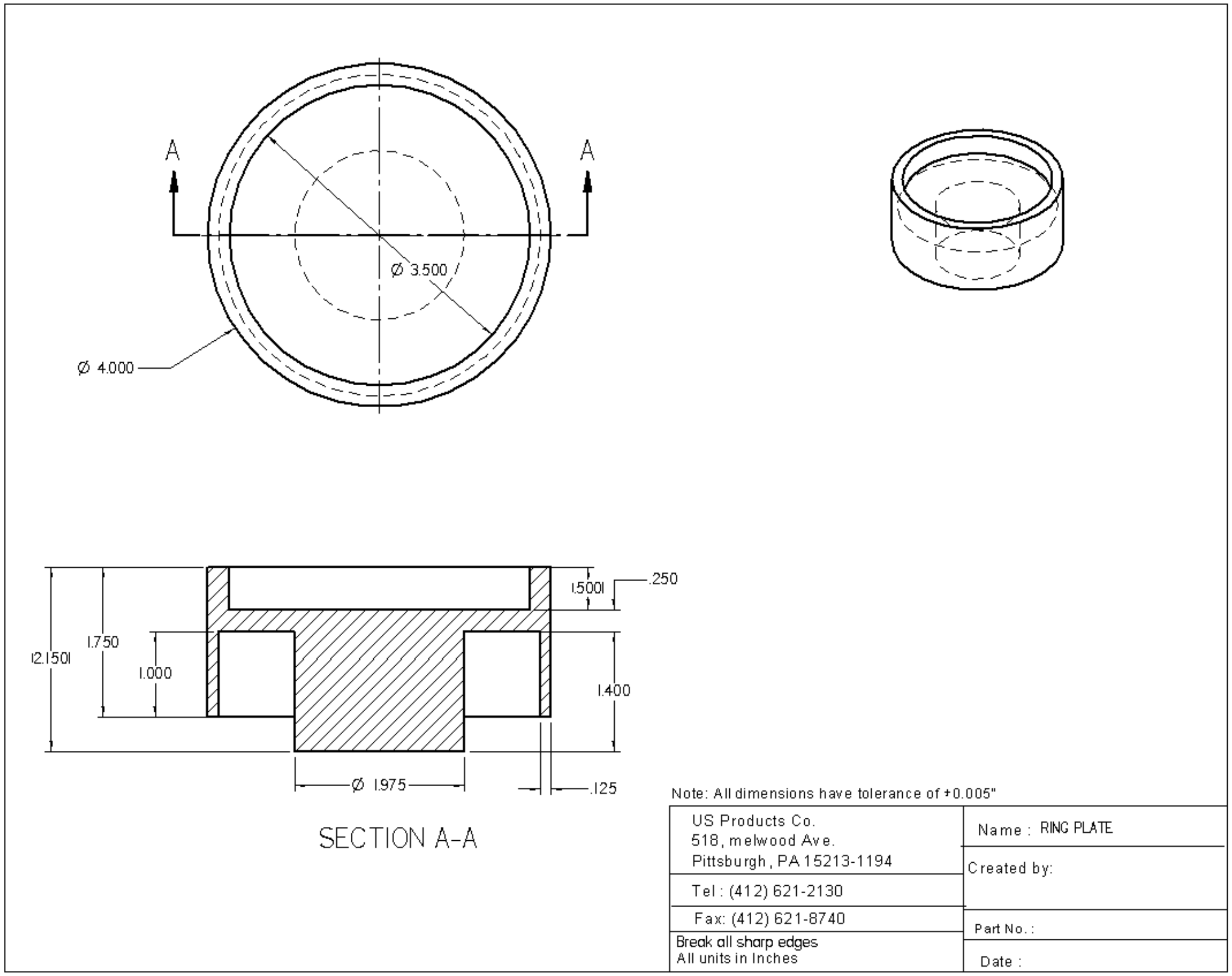



Figure 54 Ring Plate

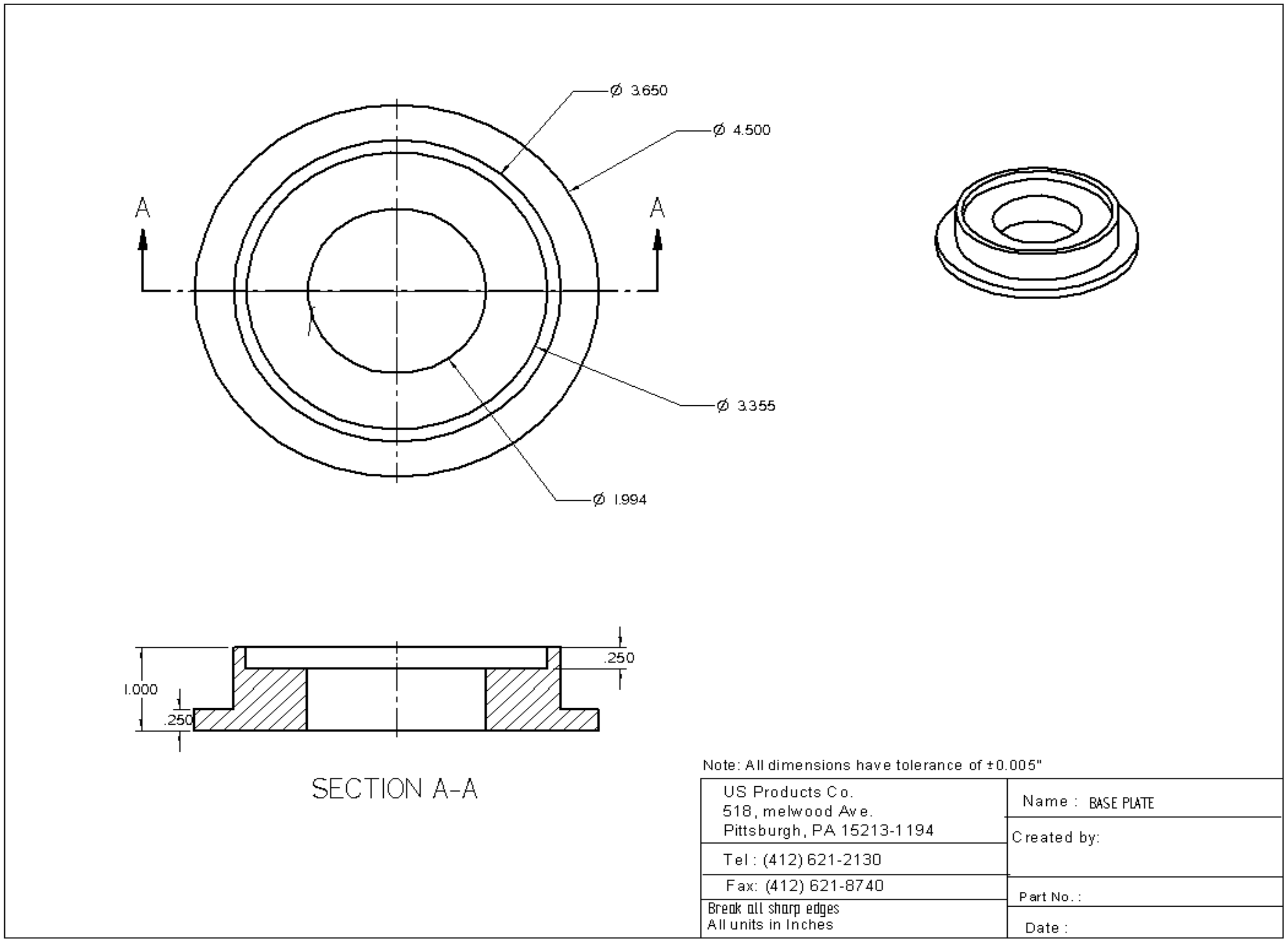



Figure 55 Base Plate

APPENDIX B

Table 47 A $2^5$ Factorial Design for Manual Lapping Experiment

| Expt. No. | Part type | Initial roughness (micro-inch) | Part diameter (in) | Grit size | | Outputs | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Rough | Finish | Flatness (lightband) | Ra (micro-inch) | Height (before lap) | Height (after lap) |
| 1 | - | + | - | - | - | | | | |
| 2 | - | + | - | - | + | | | | |
| 3 | - | + | - | + | - | | | | |
| 4 | - | + | - | + | + | | | | |
| 5 | - | + | + | - | - | | | | |
| 6 | - | + | + | - | + | | | | |
| 7 | - | + | + | + | - | | | | |
| 8 | - | + | + | + | + | | | | |
| 9 | - | - | - | - | - | | | | |
| 10 | - | - | - | - | + | | | | |
| 11 | - | - | - | + | - | | | | |
| 12 | - | - | - | + | + | | | | |
| 13 | - | - | + | - | - | | | | |
| 14 | - | - | + | - | + | | | | |
| 15 | - | - | + | + | - | | | | |
| 16 | - | - | + | + | + | | | | |
| 17 | + | + | - | - | - | | | | |
| 18 | + | + | - | - | + | | | | |
| 19 | + | + | - | + | - | | | | |
| 20 | + | + | - | + | + | | | | |
| 21 | + | + | + | - | - | | | | |
| 22 | + | + | + | - | + | | | | |
| 23 | + | + | + | + | - | | | | |
| 24 | + | + | + | + | + | | | | |
| 25 | + | - | - | - | - | | | | |
| 26 | + | - | - | - | + | | | | |
| 27 | + | - | - | + | - | | | | |
| 28 | + | - | - | + | + | | | | |
| 29 | + | - | + | - | - | | | | |
| 30 | + | - | + | - | + | | | | |
| 31 | + | - | + | + | - | | | | |
| 32 | + | - | + | + | + | | | | |

Table 48 A Complete Design Table for Manual Lapping Experiment

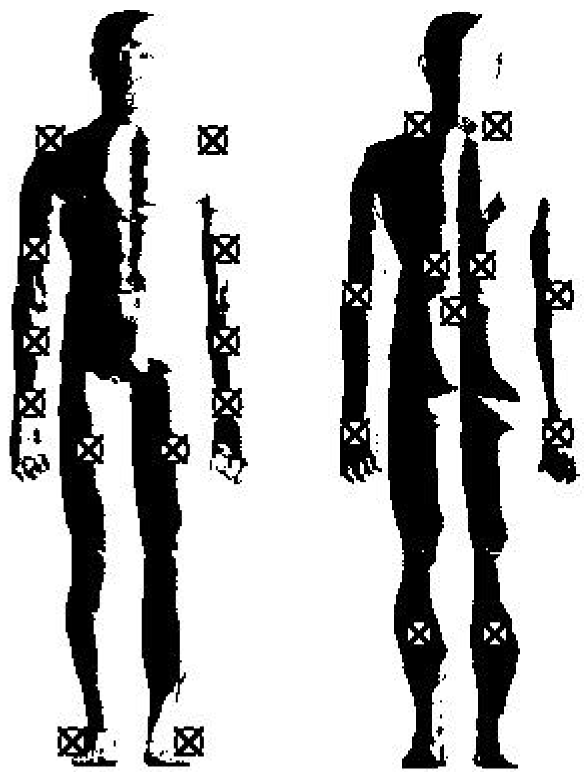
| Expt. No. | Part type | Initial roughness (micro-inch) | Part diameter (in) | Grit size | | Outputs | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Rough | Finish | Flatness (lightband) | Ra (micro-inch) | Height (before lap) | Height (after lap) |
| 1 | Disc | 32 | D1 | 220 | 500 | | | | |
| 2 | Disc | 32 | D1 | 220 | 900 | | | | |
| 3 | Disc | 32 | D1 | 320 | 500 | | | | |
| 4 | Disc | 32 | D1 | 320 | 900 | | | | |
| 5 | Disc | 32 | D2 | 220 | 500 | | | | |
| 6 | Disc | 32 | D2 | 220 | 900 | | | | |
| 7 | Disc | 32 | D2 | 320 | 500 | | | | |
| 8 | Disc | 32 | D2 | 320 | 900 | | | | |
| 9 | Disc | 12 | D1 | 220 | 500 | | | | |
| 10 | Disc | 12 | D1 | 220 | 900 | | | | |
| 11 | Disc | 12 | D1 | 320 | 500 | | | | |
| 12 | Disc | 12 | D1 | 320 | 900 | | | | |
| 13 | Disc | 12 | D2 | 220 | 500 | | | | |
| 14 | Disc | 12 | D2 | 220 | 900 | | | | |
| 15 | Disc | 12 | D2 | 320 | 500 | | | | |
| 16 | Disc | 12 | D2 | 320 | 900 | | | | |
| 17 | Nozzle | 32 | D1 | 220 | 500 | | | | |
| 18 | Nozzle | 32 | D1 | 220 | 900 | | | | |
| 19 | Nozzle | 32 | D1 | 320 | 500 | | | | |
| 20 | Nozzle | 32 | D1 | 320 | 900 | | | | |
| 21 | Nozzle | 32 | D2 | 220 | 500 | | | | |
| 22 | Nozzle | 32 | D2 | 220 | 900 | | | | |
| 23 | Nozzle | 32 | D2 | 320 | 500 | | | | |
| 24 | Nozzle | 32 | D2 | 320 | 900 | | | | |
| 25 | Nozzle | 12 | D1 | 220 | 500 | | | | |
| 26 | Nozzle | 12 | D1 | 220 | 900 | | | | |
| 27 | Nozzle | 12 | D1 | 320 | 500 | | | | |
| 28 | Nozzle | 12 | D1 | 320 | 900 | | | | |
| 29 | Nozzle | 12 | D2 | 220 | 500 | | | | |
| 30 | Nozzle | 12 | D2 | 220 | 900 | | | | |
| 31 | Nozzle | 12 | D2 | 320 | 500 | | | | |
| 32 | Nozzle | 12 | D2 | 320 | 900 | | | | |

Table 49 Data from Manual Lapping Experiment

| Expt. No. | Part type | Initial roughness (micro-inch) | Part diameter (in) | Grit size | | Outputs | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Rough | Finish | Flatness (lightband) | Ra (micro-inch) | MRR (1000th-inch/min.) |
| 1 | 1 | 2 | 1 | 1 | 1 | 4 | 3.75 | 0.053305 |
| 2 | 1 | 2 | 1 | 1 | 2 | 4 | 3.75 | 0.067295 |
| 3 | 1 | 2 | 1 | 2 | 1 | 4 | 3.75 | 0.079051 |
| 4 | 1 | 2 | 1 | 2 | 2 | 4 | 4 | 0.046419 |
| 5 | 1 | 2 | 2 | 1 | 1 | 4 | 4.25 | 0.095877 |
| 6 | 1 | 2 | 2 | 1 | 2 | 4 | 4.25 | 0.038670 |
| 7 | 1 | 2 | 2 | 2 | 1 | 4 | 3.75 | 0.067295 |
| 8 | 1 | 2 | 2 | 2 | 2 | 4 | 4.25 | 0.038911 |
| 9 | 1 | 1 | 1 | 1 | 1 | 4 | 2 | 0.087848 |
| 10 | 1 | 1 | 1 | 1 | 2 | 4 | 2 | 0.451128 |
| 11 | 1 | 1 | 1 | 2 | 1 | 4 | 2 | 0.094451 |
| 12 | 1 | 1 | 1 | 2 | 2 | 4 | 2 | 0.130378 |
| 13 | 1 | 1 | 2 | 1 | 1 | 2 | 3.75 | 0.192802 |
| 14 | 1 | 1 | 2 | 1 | 2 | 2 | 3.75 | 0.109409 |
| 15 | 1 | 1 | 2 | 2 | 1 | 2 | 3.75 | 0.429066 |
| 16 | 1 | 1 | 2 | 2 | 2 | 2 | 3.75 | 0.215589 |
| 17 | 2 | 2 | 1 | 1 | 1 | 4 | 4.25 | 0.057471 |
| 18 | 2 | 2 | 1 | 1 | 2 | 4 | 4.25 | 0.194099 |
| 19 | 2 | 2 | 1 | 2 | 1 | 4 | 4.25 | 0.050251 |
| 20 | 2 | 2 | 1 | 2 | 2 | 4 | 4.25 | 0.334528 |
| 21 | 2 | 2 | 2 | 1 | 1 | 2 | 8 | 0.127660 |
| 22 | 2 | 2 | 2 | 1 | 2 | 2 | 8.25 | 0.136799 |
| 23 | 2 | 2 | 2 | 2 | 1 | 2 | 8 | 0.139860 |
| 24 | 2 | 2 | 2 | 2 | 2 | 2 | 8 | 0.128068 |
| 25 | 2 | 1 | 1 | 1 | 1 | 4 | 4.25 | 0.159067 |
| 26 | 2 | 1 | 1 | 1 | 2 | 4 | 4.25 | 0.059737 |
| 27 | 2 | 1 | 1 | 2 | 1 | 4 | 4.25 | 0.116686 |
| 28 | 2 | 1 | 1 | 2 | 2 | 4 | 4.25 | 0.160000 |
| 29 | 2 | 1 | 2 | 1 | 1 | 3.5 | 2.25 | 0.112676 |
| 30 | 2 | 1 | 2 | 1 | 2 | 3.5 | 2.25 | 0.113208 |
| 31 | 2 | 1 | 2 | 2 | 1 | 3.5 | 2.25 | 0.116883 |
| 32 | 2 | 1 | 2 | 2 | 2 | 3.5 | 2.25 | 0.112613 |

Table 50 Data from Manual Lapping Experiment with a Transformed MRR ($MRR^*$) Column

| Expt. No. | Part type | Initial roughness (micro-inch) | Part diameter (in) | Grit size | | Outputs | | | MRR* [ln(MRR)] |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Rough | Finish | Flatness (lightband) | Ra (micro-inch) | MRR (1000th-inch/min.) | |
| 1 | 1 | 2 | 1 | 1 | 1 | 4 | 3.75 | 0.053305 | -2.931726944 |
| 2 | 1 | 2 | 1 | 1 | 2 | 4 | 3.75 | 0.067295 | -2.698673039 |
| 3 | 1 | 2 | 1 | 2 | 1 | 4 | 3.75 | 0.079051 | -2.537657215 |
| 4 | 1 | 2 | 1 | 2 | 2 | 4 | 4 | 0.046419 | -3.070044307 |
| 5 | 1 | 2 | 2 | 1 | 1 | 4 | 4.25 | 0.095877 | -2.344686269 |
| 6 | 1 | 2 | 2 | 1 | 2 | 4 | 4.25 | 0.038670 | -3.252697373 |
| 7 | 1 | 2 | 2 | 2 | 1 | 4 | 3.75 | 0.067295 | -2.698673039 |
| 8 | 1 | 2 | 2 | 2 | 2 | 4 | 4.25 | 0.038911 | -3.246490992 |
| 9 | 1 | 1 | 1 | 1 | 1 | 4 | 2 | 0.087848 | -2.432150297 |
| 10 | 1 | 1 | 1 | 1 | 2 | 4 | 2 | 0.451128 | -0.796004566 |
| 11 | 1 | 1 | 1 | 2 | 1 | 4 | 2 | 0.094451 | -2.35967406 |
| 12 | 1 | 1 | 1 | 2 | 2 | 4 | 2 | 0.130378 | -2.037316615 |
| 13 | 1 | 1 | 2 | 1 | 1 | 2 | 3.75 | 0.192802 | -1.64609123 |
| 14 | 1 | 1 | 2 | 1 | 2 | 2 | 3.75 | 0.109409 | -2.212660385 |
| 15 | 1 | 1 | 2 | 2 | 1 | 2 | 3.75 | 0.429066 | -0.846145123 |
| 16 | 1 | 1 | 2 | 2 | 2 | 2 | 3.75 | 0.215589 | -1.534382746 |
| 17 | 2 | 2 | 1 | 1 | 1 | 4 | 4.25 | 0.057471 | -2.856470206 |
| 18 | 2 | 2 | 1 | 1 | 2 | 4 | 4.25 | 0.194099 | -1.639384989 |
| 19 | 2 | 2 | 1 | 2 | 1 | 4 | 4.25 | 0.050251 | -2.990719732 |
| 20 | 2 | 2 | 1 | 2 | 2 | 4 | 4.25 | 0.334528 | -1.095034467 |
| 21 | 2 | 2 | 2 | 1 | 1 | 2 | 8 | 0.127660 | -2.058388132 |
| 22 | 2 | 2 | 2 | 1 | 2 | 2 | 8.25 | 0.136799 | -1.989243274 |
| 23 | 2 | 2 | 2 | 2 | 1 | 2 | 8 | 0.139860 | -1.967112357 |
| 24 | 2 | 2 | 2 | 2 | 2 | 2 | 8 | 0.128068 | -2.055191539 |
| 25 | 2 | 1 | 1 | 1 | 1 | 4 | 4.25 | 0.159067 | -1.838430989 |
| 26 | 2 | 1 | 1 | 1 | 2 | 4 | 4.25 | 0.059737 | -2.817801065 |
| 27 | 2 | 1 | 1 | 2 | 1 | 4 | 4.25 | 0.116686 | -2.148267733 |
| 28 | 2 | 1 | 1 | 2 | 2 | 4 | 4.25 | 0.160000 | -1.832581464 |
| 29 | 2 | 1 | 2 | 1 | 1 | 3.5 | 2.25 | 0.112676 | -2.183238335 |
| 30 | 2 | 1 | 2 | 1 | 2 | 3.5 | 2.25 | 0.113208 | -2.178532444 |
| 31 | 2 | 1 | 2 | 2 | 1 | 3.5 | 2.25 | 0.116883 | -2.146580845 |
| 32 | 2 | 1 | 2 | 2 | 2 | 3.5 | 2.25 | 0.112613 | -2.183801557 |



| | | | |
|---|---|---|---|
| | Head | | Neck |
| 7 | Left Shoulder | 8 | Right Shoulder |
| 7 | Left Trapezius | 8 | Right Trapezius |
| | Chest | | Thoracic |
| 8 | Left Upper Arm | 9 | Right Upper Arm |
| 8 | Left Elbow | 8 | Right Elbow |
| 8 | Left Forearm | 9 | Right Forearm |
| 8 | Left Wrist | 10 | Right Wrist |
| 10 | Left Hand | 10 | Right Hand |
| | Abdomen | 7 | Lumbar |
| 7 | Left Erector Sp. | 7 | Right Erector Sp. |
| | Left Gluteus | | Right Gluteus |
| | Left Hip | | Right Hip |
| 6 | Left Thigh | 6 | Right Thigh |
| | Left Knee | | Right Knee |
| 8 | Left Lower Leg | 8 | Right Lower Leg |
| 9 | Left Foot | 9 | Right Foot |

0 — 10
No Discomfort — Severe Discomfort

Maximum Observed Heart Rate: (75% of age predicted max heart rate)
Rating of Perceived Exertion: 14 (on a scale of 6 to 20)

*ErgoMaster™*

Figure 56 Discomfort Analysis on Body Parts with respect to Manual Lapping

Table 51 A $2^{6-1}$ Fractional Factorial Design for Mechanical Lapping

| | A | B | C | D | E | F=ABCDE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Expt. No. | Part type | RPM | Initial roughness (micro-inch) | Part Dia. or Seat width (in) | Abrasive grit size | | Outputs | | | |
| | | | | | Rough | Finish | Flatness (lightband) | Ra (micro-inch) | Time Taken | Removed Material |
| 1 | - | - | - | - | - | - | | | | |
| 2 | - | + | - | - | - | + | | | | |
| 3 | - | - | - | - | + | + | | | | |
| 4 | - | + | - | - | + | - | | | | |
| 5 | - | - | + | - | - | + | | | | |
| 6 | - | + | + | - | - | - | | | | |
| 7 | - | - | + | - | + | - | | | | |
| 8 | - | + | + | - | + | + | | | | |
| 9 | - | - | + | + | - | - | | | | |
| 10 | - | + | + | + | - | + | | | | |
| 11 | - | - | + | + | + | + | | | | |
| 12 | - | + | + | + | + | - | | | | |
| 13 | - | - | - | + | - | + | | | | |
| 14 | - | + | - | + | - | - | | | | |
| 15 | - | - | - | + | + | - | | | | |
| 16 | - | + | - | + | + | + | | | | |
| 17 | + | - | + | + | - | + | | | | |
| 18 | + | + | + | + | - | - | | | | |
| 19 | + | - | + | + | + | - | | | | |
| 20 | + | + | + | + | + | + | | | | |
| 21 | + | - | - | + | - | - | | | | |
| 22 | + | + | - | + | - | + | | | | |
| 23 | + | - | - | + | + | + | | | | |
| 24 | + | + | - | + | + | - | | | | |
| 25 | + | - | - | - | - | + | | | | |
| 26 | + | + | - | - | - | - | | | | |
| 27 | + | - | - | - | + | - | | | | |
| 28 | + | + | - | - | + | + | | | | |
| 29 | + | - | + | - | - | - | | | | |
| 30 | + | + | + | - | - | + | | | | |
| 31 | + | - | + | - | + | + | | | | |
| 32 | + | + | + | - | + | - | | | | |

Table 52 A Complete Design Table for Mechanical Lapping

| | A | B | C | D | E | F=ABCDE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Expt. No. | Part type | RPM | Initial roughness (micro-inch) | Part Dia. or Seat width (in) | Abrasive grit size | | Outputs | | | |
| | | | | | Rough | Finish | Flatness (lightband) | Ra (micro-inch) | Time Taken | Removed Material |
| 1 | Disc | 70 | 32 | D1 | 220 | 500 | | | | |
| 2 | Disc | 80 | 32 | D1 | 220 | 900 | | | | |
| 3 | Disc | 70 | 32 | D1 | 320 | 900 | | | | |
| 4 | Disc | 80 | 32 | D1 | 320 | 500 | | | | |
| 5 | Disc | 70 | 64 | D1 | 220 | 900 | | | | |
| 6 | Disc | 80 | 64 | D1 | 220 | 500 | | | | |
| 7 | Disc | 70 | 64 | D1 | 320 | 500 | | | | |
| 8 | Disc | 80 | 64 | D1 | 320 | 900 | | | | |
| 9 | Disc | 70 | 64 | D2 | 220 | 500 | | | | |
| 10 | Disc | 80 | 64 | D2 | 220 | 900 | | | | |
| 11 | Disc | 70 | 64 | D2 | 320 | 900 | | | | |
| 12 | Disc | 80 | 64 | D2 | 320 | 500 | | | | |
| 13 | Disc | 70 | 32 | D2 | 220 | 900 | | | | |
| 14 | Disc | 80 | 32 | D2 | 220 | 500 | | | | |
| 15 | Disc | 70 | 32 | D2 | 320 | 500 | | | | |
| 16 | Disc | 80 | 32 | D2 | 320 | 900 | | | | |
| 17 | Nozzle | 70 | 64 | D2 | 220 | 900 | | | | |
| 18 | Nozzle | 80 | 64 | D2 | 220 | 500 | | | | |
| 19 | Nozzle | 70 | 64 | D2 | 320 | 500 | | | | |
| 20 | Nozzle | 80 | 64 | D2 | 320 | 900 | | | | |
| 21 | Nozzle | 70 | 32 | D2 | 220 | 500 | | | | |
| 22 | Nozzle | 80 | 32 | D2 | 220 | 900 | | | | |
| 23 | Nozzle | 70 | 32 | D2 | 320 | 900 | | | | |
| 24 | Nozzle | 80 | 32 | D2 | 320 | 500 | | | | |
| 25 | Nozzle | 70 | 32 | D1 | 220 | 900 | | | | |
| 26 | Nozzle | 80 | 32 | D1 | 220 | 500 | | | | |
| 27 | Nozzle | 70 | 32 | D1 | 320 | 500 | | | | |
| 28 | Nozzle | 80 | 32 | D1 | 320 | 900 | | | | |
| 29 | Nozzle | 70 | 64 | D1 | 220 | 500 | | | | |
| 30 | Nozzle | 80 | 64 | D1 | 220 | 900 | | | | |
| 31 | Nozzle | 70 | 64 | D1 | 320 | 900 | | | | |
| 32 | Nozzle | 80 | 64 | D1 | 320 | 500 | | | | |

Table 53 Data Obtained from Mechanical Lapping Experiments

| Expt. No. | Part type | RPM | Initial roughness (micro-inch) | Part diameter (in) | Part Dia. or Seat width (in) | Abrasive grit size | | Outputs | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Rough | Finish | Flatness (lightband) | Ra (micro-inch) | MRR (1000th-inch/min) |
| 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 4 | 8 | 0.6266 |
| 2 | 1 | 2 | 1 | 2 | 1 | 1 | 2 | 3.5 | 7.75 | 0.5279 |
| 3 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 3.5 | 10.5 | 0.6637 |
| 4 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 3 | 8 | 0.6349 |
| 5 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 2.5 | 7.5 | 0.5085 |
| 6 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 8 | 0.4438 |
| 7 | 1 | 1 | 2 | 2 | 1 | 2 | 1 | 2 | 8.5 | 0.9567 |
| 8 | 1 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 8 | 0.3689 |
| 9 | 1 | 1 | 2 | 1 | 2 | 1 | 1 | 2.5 | 4.25 | 0.0681 |
| 10 | 1 | 2 | 2 | 1 | 2 | 1 | 2 | 3 | 4.25 | 0.1500 |
| 11 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 4 | 0.0093 |
| 12 | 1 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 4.25 | 0.2236 |
| 13 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 4 | 0.1661 |
| 14 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 3.75 | 0.1615 |
| 15 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 2 | 3.75 | 0.0667 |
| 16 | 1 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 4 | 0.3751 |
| 17 | 2 | 1 | 2 | 2 | 2 | 1 | 2 | 3.5 | 5.75 | 0.4242 |
| 18 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 4 | 8 | 0.1250 |
| 19 | 2 | 1 | 2 | 2 | 2 | 2 | 1 | 3 | 3.75 | 0.6154 |
| 20 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 4 | 6 | 0.1630 |
| 21 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 3 | 4.25 | 0.0465 |
| 22 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 3 | 4.25 | 0.6222 |
| 23 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 3.5 | 5.75 | 0.0707 |
| 24 | 2 | 2 | 1 | 2 | 2 | 2 | 1 | 3 | 4.25 | 0.4574 |
| 25 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 5.75 | 0.1124 |
| 26 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 5.5 | 0.1485 |
| 27 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 6 | 0.1689 |
| 28 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 2.5 | 6.75 | 0.1942 |
| 29 | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 6.25 | 0.2335 |
| 30 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 6.5 | 0.2055 |
| 31 | 2 | 1 | 2 | 1 | 1 | 2 | 2 | 2 | 6.5 | 0.3960 |
| 32 | 2 | 2 | 2 | 1 | 1 | 2 | 1 | 2 | 6 | 0.5405 |

Table 54 Alias Relationships for $2_{VI}^{6-1}$ Fractional Factorial Designs[83]

$I = ABCDEF$

<u>Aliases</u>

Each main effect is aliased with a single 5-factor interaction.
Each 2-factor interaction is aliased with a single 4-factor interaction.

$ABC = DEF$ $\quad ACE = BDF$
$ABD = CEF$ $\quad ACF = BDE$
$ABE = CDF$ $\quad ADE = BCF$
$ABF = CDE$ $\quad ADF = BCE$
$ACD = BEF$ $\quad AEF = BCD$

2 blocks of 16: $ABF = CDE$    4 blocks of 8: $BC$
$ABF = CDE$
$ACF = BDE$

# APPENDIX C

# VARIABLES

- Des_Rough = Desired Surface Roughness (Module-I)
- MRR = Material Removal Rate (Module-I)
- Des_Flatness = Desired Surface Flatness (Module-I)
- Tolerance = Tolerance (Module-I)
- DsrdRa = Desired Surface Roughness (Module-II)
- PreRa = Initial Surface Roughness (Module-II)
- DsrdFlt = Desired Surface Flatness (Module-II)
- PreFlat = Initial Surface Flatness (Module-II)
- MRR = Material Removal Rate (Module-II)
- WPMatrl = Workpiece Material (Module-II)
- xLow = Extremely Low
- vrLow = Very Low
- Low = Low
- vClose = Very Close
- Close = Close
- xFlat = Extremely Flat
- vrFlat = Very Flat
- mFlat = Medium Flat
- Flat = Flat
- spFinish = Super Finish
- Finish = Finish
- HiFinish = Hi Finish
- NrFinish = Normal Finish
- RoFinish = Rough Finish
- MCS = Metal-Carbon-Stainless

**RULEBASE Module-I of the Preliminary Advisory System**

```
RULE Rule1
   IF (MRR IS XLOW) AND (Tolerance IS XCLOSE) THEN
      Process = Lapping
END

RULE Rule2
   IF (MRR IS LOW) AND (Tolerance IS CLOSE) THEN
      Process = Others
END

RULE Rule3
   IF (MRR IS LOW) AND (Tolerance IS XCLOSE) THEN
      Process = Lapping
END

RULE Rule4
   IF (MRR IS XLOW) AND (Tolerance IS CLOSE) THEN
      Process = Others
END

RULE Rule5
   IF (Des_Flatness IS XFLAT) AND (Tolerance IS XCLOSE) THEN
      Process = Lapping
END

RULE Rule6
   IF (Des_Flatness IS FLAT) AND (Tolerance IS XCLOSE) THEN
      Process = Lapping
END

RULE Rule7
   IF (Des_Flatness IS XFLAT) AND (Tolerance IS CLOSE) THEN
      Process = Lapping
END

RULE Rule8
   IF (Des_Flatness IS FLAT) AND (Tolerance IS CLOSE) THEN
      Process = Others
END

RULE Rule9
   IF (Des_Rough IS SPFinish) AND (Tolerance IS XCLOSE) THEN
```

```
      Process = Lapping
END

RULE Rule10
   IF (Des_Rough IS Finish) AND (Tolerance IS XCLOSE) THEN
      Process = Others
END

RULE Rule11
   IF (Des_Rough IS Finish) AND (Tolerance IS CLOSE) THEN
      Process = Others
END

RULE Rule12
   IF (Des_Rough IS SPFinish) AND (Tolerance IS CLOSE) THEN
      Process = Lapping
END

RULE Rule13
   IF (MRR IS XLOW) AND (Des_Flatness IS XFLAT) THEN
      Process = Lapping
END

RULE Rule14
   IF (MRR IS LOW) AND (Des_Flatness IS XFLAT) THEN
      Process = Lapping
END

RULE Rule15
   IF (MRR IS LOW) AND (Des_Flatness IS FLAT) THEN
      Process = Others
END

RULE Rule16
   IF (MRR IS XLOW) AND (Des_Flatness IS FLAT) THEN
      Process = Lapping
END

RULE Rule17
   IF (MRR IS XLOW) AND (Des_Rough IS SPFinish) THEN
      Process = Lapping
END
```

```
  RULE Rule18
    IF (MRR IS XLOW) AND (Des_Rough IS Finish) THEN
      Process = Others
  END

  RULE Rule19
    IF (MRR IS LOW) AND (Des_Rough IS SPFinish) THEN
      Process = Others
  END

  RULE Rule20
    IF (MRR IS LOW) AND (Des_Rough IS Finish) THEN
      Process = Others
  END
END
```

**<u>RULEBASE Module-II of the Preliminary Advisory System</u>**

RULE 1
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 2
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 3
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 4
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 5
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 6
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)

AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 7
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 8
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 9
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 10
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 11
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200

END

RULE 12
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 13
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 14
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 15
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 16
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 17
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)

AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 18
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 19
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 20
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 21
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 22
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
AND Grit_Size_B = 500 AND Grit_Size_C = 1200

END

RULE 23

IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 24

IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 25

IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 26

IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 27

IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 28

IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)

AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 29
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 30
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 31
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 32
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 33
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200

END

RULE 34
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 35
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 36
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 37
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 38
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 39
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)

AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 40
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 41
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 42
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 43
IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 44
IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
THEN
Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
AND Grit_Size_B = 500 AND Grit_Size_C = 1200

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    END

RULE 45
    IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
      AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
    THEN
      Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
      AND Grit_Size_B = 500 AND Grit_Size_C = 1200
    END

RULE 46
    IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
      AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
    THEN
      Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
      AND Grit_Size_B = 500 AND Grit_Size_C = 1200
    END

RULE 47
    IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
      AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
    THEN
      Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
      AND Grit_Size_B = 500 AND Grit_Size_C = 1200
    END

RULE 48
    IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
      AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
    THEN
      Abrasive Type = White Aluminum Oxide AND Grit_Size_A = 220
      AND Grit_Size_B = 500 AND Grit_Size_C = 1200
    END

RULE 49
    IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
      AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
    THEN
      Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
      AND Grit_Size_B = 500 AND Grit_Size_C = 1200
    END

RULE 50
    IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
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   AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
 THEN
   Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
   AND Grit_Size_B = 500 AND Grit_Size_C = 1200
 END

RULE 51
  IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
   AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
 THEN
   Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
   AND Grit_Size_B = 500 AND Grit_Size_C = 1200
 END

RULE 52
  IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
   AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS MCS)
 THEN
   Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
   AND Grit_Size_B = 500 AND Grit_Size_C = 1200
 END

RULE 53
  IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
   AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS MCS)
 THEN
   Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
   AND Grit_Size_B = 500 AND Grit_Size_C = 1200
 END

RULE 54
  IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
   AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS MCS)
 THEN
   Abrasive Type = White Aluminum Oxide AND Grit_Size_A = None
   AND Grit_Size_B = 500 AND Grit_Size_C = 1200
 END

RULE 55
  IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
   AND (PreFlat IS xFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
 THEN
   Abrasive Type = Garnet AND Grit_Size_A = None
   AND Grit_Size_B = 600 AND Grit_Size_C = 1000
```

END

RULE 56
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = None
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 57
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = None
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 58
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 59
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 60
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 61
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)

AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 62
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 63
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 64
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 65
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 66
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000

END

RULE 67
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 68
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 69
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 70
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = None
AND Grit_Size_B = 800 AND Grit_Size_C = 1000
END

RULE 71
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = None
AND Grit_Size_B = 800 AND Grit_Size_C = 1000
END

RULE 72
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)

AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = None
AND Grit_Size_B = 800 AND Grit_Size_C = 1000
END

RULE 73
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = None
AND Grit_Size_B = 900 AND Grit_Size_C = 1200
END

RULE 74
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 75
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 76
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 77
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000

END

RULE 78
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 500 AND Grit_Size_C = 1200
END

RULE 79
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 80
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 81
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 82
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 83
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)

AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 84
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 85
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 86
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 87
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 88
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = None
AND Grit_Size_B = 800 AND Grit_Size_C = 1000

END

RULE 89
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = None
AND Grit_Size_B = 800 AND Grit_Size_C = 1000
END

RULE 90
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = None
AND Grit_Size_B = 800 AND Grit_Size_C = 1000
END

RULE 91
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 92
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 93
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 94
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)

AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 95
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 96
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 97
IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 98
IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 99
IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000

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    END

RULE 100
    IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
      AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
    THEN
       Abrasive Type = Garnet AND Grit_Size_A = 220
      AND Grit_Size_B = 600 AND Grit_Size_C = 1000
    END

RULE 101
    IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
      AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
    THEN
       Abrasive Type = Garnet AND Grit_Size_A = 220
      AND Grit_Size_B = 600 AND Grit_Size_C = 1000
    END

RULE 102
    IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
      AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
    THEN
       Abrasive Type = Garnet AND Grit_Size_A = 220
      AND Grit_Size_B = 600 AND Grit_Size_C = 1000
    END

RULE 103
    IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
      AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
    THEN
       Abrasive Type = Garnet AND Grit_Size_A = 220
      AND Grit_Size_B = 600 AND Grit_Size_C = 1000
    END

RULE 104
    IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
      AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
    THEN
       Abrasive Type = Garnet AND Grit_Size_A = 220
      AND Grit_Size_B = 600 AND Grit_Size_C = 1000
    END

RULE 105
    IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
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AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 106
IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 107
IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 108
IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS BrassBronze)
THEN
Abrasive Type = Garnet AND Grit_Size_A = 220
AND Grit_Size_B = 600 AND Grit_Size_C = 1000
END

RULE 109
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 110
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron

END

RULE 111
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 112
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 9 Micron AND Grit_Size_C = 3 Micron
END

RULE 113
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 9 Micron AND Grit_Size_C = 3 Micron
END

RULE 114
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 9 Micron AND Grit_Size_C = 3 Micron
END

RULE 115
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 116
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)

AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 117
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 118
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 119
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 120
IF (DsrdRa IS SPFinish) AND (PreRa IS SPFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 121
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron

END

RULE 122
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 123
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 124
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 9 Micron AND Grit_Size_C = 3 Micron
END

RULE 125
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 9 Micron AND Grit_Size_C = 3 Micron
END

RULE 126
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 9 Micron AND Grit_Size_C = 3 Micron
END

RULE 127
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)

AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 128
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 129
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 130
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 131
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 132
IF (DsrdRa IS SPFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron

END

RULE 133
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 134
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 135
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS xFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 136
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 6 Micron AND Grit_Size_C = 3 Micron
END

RULE 137
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 6 Micron AND Grit_Size_C = 3 Micron
END

RULE 138
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS xFlat)

AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 6 Micron AND Grit_Size_C = 3 Micron
END

RULE 139
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 140
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 141
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 142
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 6 Micron AND Grit_Size_C = 3 Micron
END

RULE 143
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 6 Micron AND Grit_Size_C = 3 Micron

END

RULE 144
IF (DsrdRa IS HiFinish) AND (PreRa IS HiFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 6 Micron AND Grit_Size_C = 3 Micron
END

RULE 145
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 146
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 147
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 3 Micron
END

RULE 148
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 6 Micron AND Grit_Size_C = 3 Micron
END

RULE 149
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)

AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 6 Micron AND Grit_Size_C = 3 Micron
END

RULE 150
IF (DsrdRa IS HiFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = 6 Micron AND Grit_Size_C = 3 Micron
END

RULE 151
IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 6 Micron
END

RULE 152
IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 6 Micron
END

RULE 153
IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 6 Micron
END

RULE 154
IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 6 Micron

END

RULE 155
IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 6 Micron
END

RULE 156
IF (DsrdRa IS NrFinish) AND (PreRa IS NrFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 6 Micron
END

RULE 157
IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 6 Micron
END

RULE 158
IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 6 Micron
END

RULE 159
IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS vrFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 6 Micron
END

RULE 160
IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)

AND (PreFlat IS mFlat) AND (MRR IS xLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 6 Micron
END

RULE 161
IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS vrLow) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 6 Micron
END

RULE 162
IF (DsrdRa IS NrFinish) AND (PreRa IS RoFinish) AND (DsrdFlt IS vrFlat)
AND (PreFlat IS mFlat) AND (MRR IS Low) AND (WPMatrl IS HardFace)
THEN
Abrasive Type = Diamond AND Grit_Size_A = None
AND Grit_Size_B = None AND Grit_Size_C = 6 Micron
END

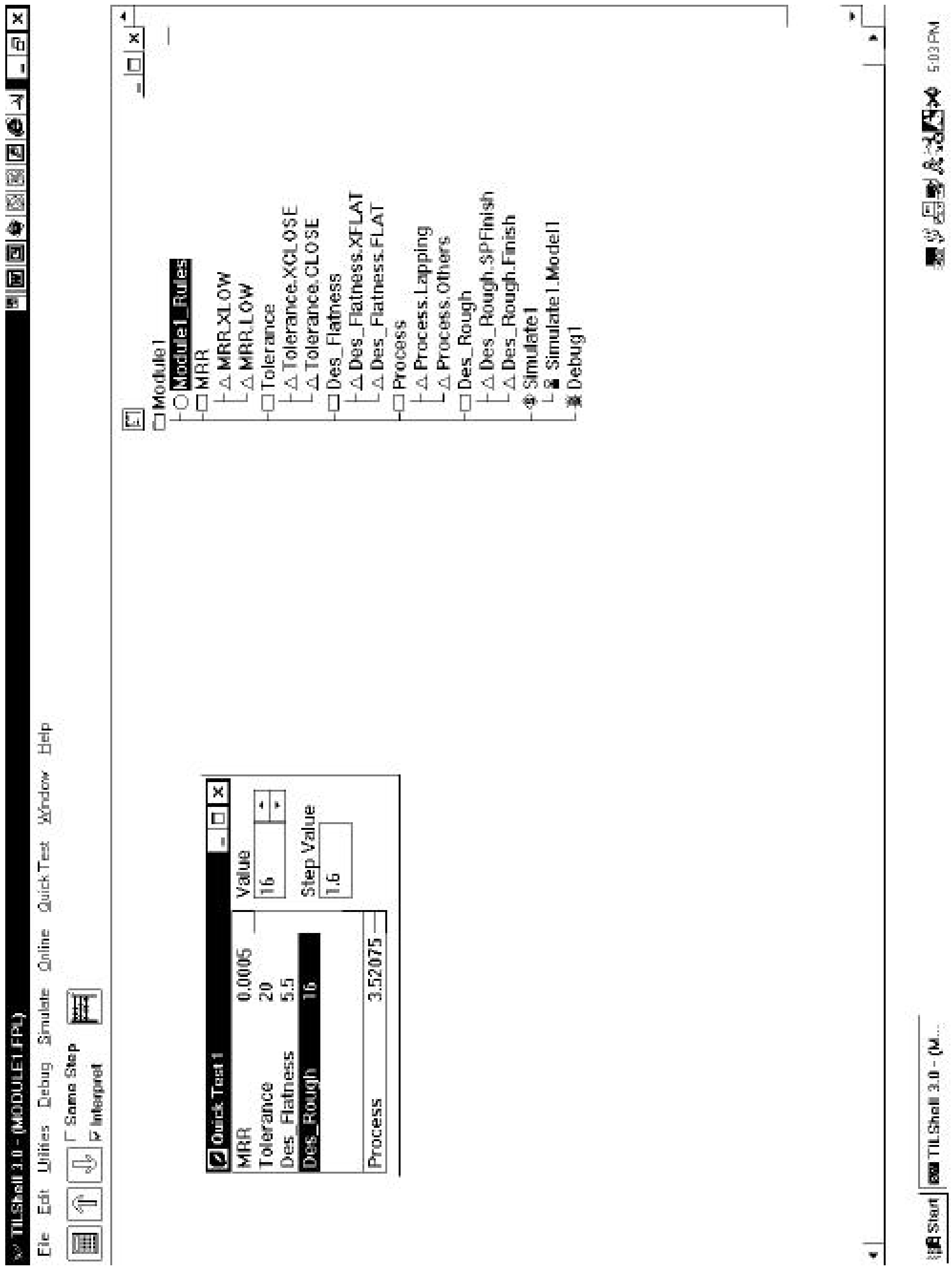


Figure 57 A Sample Working Screen of Module-I

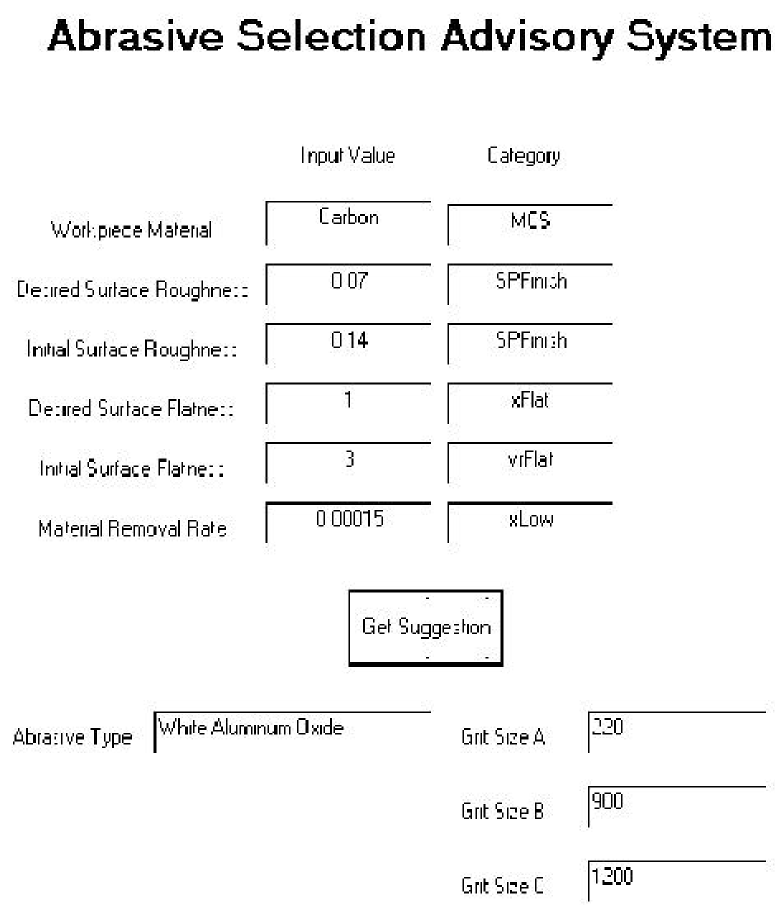


Figure 58 Sample Working Screen of Module-II

Table 55 Examples of System Outputs and Experts' Responses Comparison (Module-II)

| System Inputs | | | | | | System Outputs | Experts' Responses |
|---|---|---|---|---|---|---|---|
| **Seat Material** | **Desired Roughness (mm)** | **Initial Roughness (mm)** | **Desired Flatness (Lightband)** | **Initial Flatness (Lightband)** | **MRR ($in^3$/in/min)** | **Abrasive Type and Grit size(s)** | **Abrasive Type and Grit size(s)** |
| Metal | 0.05 | 0.12 | 1 | 1.4 | 0.0001 | White Aluminum Oxide, 900, 1200 | White Aluminum Oxide, 500, 1000 |
| Carbon | 0.07 | 0.14 | 1 | 3 | 0.00015 | White Aluminum Oxide, 220, 900, 1200 | White Aluminum Oxide, 220, 900, 1200 |
| Stainless | 0.1 | 0.15 | 2.5 | 5 | 0.00005 | White Aluminum Oxide, 500, 1200 | White Aluminum Oxide, 500, 1200 |
| Metal | 0.14 | 0.2 | 1 | 3 | 0.00005 | White Aluminum Oxide, 220, 500, 1200 | White Aluminum Oxide, 500, 1200 |
| Carbon | 0.05 | 0.25 | 3 | 5 | 0.00025 | White Aluminum Oxide, 500, 1200 | White Aluminum Oxide, 220, 500, 1200 |
| Stainless | 0.2 | 0.3 | 2 | 4 | 0.0001 | White Aluminum Oxide, 500, 1200 | White Aluminum Oxide, 500, 1200 |
| Metal | 0.2 | 0.3 | 3 | 5 | 0.00007 | White Aluminum Oxide, 500, 1200 | White Aluminum Oxide, 220, 500, 1200 |
| Carbon | 0.2 | 0.5 | 3.5 | 6 | 0.00012 | White Aluminum Oxide, 220, 500, 1200 | White Aluminum Oxide, 220, 500, 1200 |
| Stainless | 0.4 | 0.5 | 2 | 4 | 0.0004 | White Aluminum Oxide, 220, 500, 1200 | White Aluminum Oxide, 220, 500, 1200 |
| Metal | 0.4 | 0.8 | 2 | 4 | 0.0004 | White Aluminum Oxide, 500, 1200 | White Aluminum Oxide, 220, 500, 1200 |
| Brass | 0.05 | 0.1 | 1 | 1.5 | 0.00025 | Garnet, 600, 1000 | Garnet, 600, 1000 |
| Brass | 0.03 | 0.15 | 1 | 3 | 0.0004 | Garnet, 220, 600, 1000 | Garnet, 220, 600, 1000 |
| Bronze | 0.045 | 0.1 | 3 | 5 | 0.0002 | Garnet, 220, 600, 1000 | Garnet, 220, 600, 1000 |
| | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Bronze | 0.06 | 0.2 | 1 | 1.6 | 0.00025 | Garnet, 220, 600, 1000 | Garnet, 220, 600, 1000 |
| Brass | 0.1 | 0.2 | 2 | 3 | 0.00015 | Garnet, 220, 600, 1000 | Garnet, 220, 600, 1000 |
| Brass | 0.05 | 0.3 | 3 | 5 | 0.0001 | Garnet, 220, 600, 1000 | Garnet, 220, 600, 1000 |
| Bronze | 0.2 | 0.3 | 1.25 | 1.6 | 0.0004 | Garnet, 220, 600, 1000 | Garnet, 220, 600, 1000 |
| Brass | 0.25 | 0.3 | 2 | 5 | 0.00025 | Garnet, 800, 1000 | Garnet, 600, 1000 |
| Brass | 0.3 | 0.5 | 3 | 6 | 0.00045 | Garnet, 220, 600, 1000 | Garnet, 220, 600, 1000 |
| Bronze | 0.4 | 0.8 | 3 | 4 | 0.0004 | Garnet, 220, 600, 1000 | Garnet, 220, 600, 1000 |
| Hard Face | 0.05 | 0.1 | 1 | 1.5 | 0.00025 | Diamond, 3 Micron | Diamond, 3 Micron |
| Hard Face | 0.025 | 0.05 | 1 | 2 | 0.0004 | Diamond, 9 Micron, 3 Micron | Diamond, 9 Micron, 3 Micron |
| Hard Face | 0.04 | 0.1 | 3 | 5 | 0.00025 | Diamond, 3 Micron | Diamond, 3 Micron |
| Hard Face | 0.1 | 0.2 | 1 | 3 | 0.00027 | Diamond, 9 Micron, 3 Micron | Diamond, 9 Micron, 3 Micron |
| Hard Face | 0.12 | 0.3 | 3 | 5 | 0.00015 | Diamond, 3 Micron | Diamond, 9 Micron, 3 Micron |
| Hard Face | 0.2 | 0.3 | 1 | 3 | 0.00025 | Diamond, 6 Micron, 3 Micron | Diamond, 9 Micron, 3 Micron |
| Hard Face | 0.25 | 0.3 | 2 | 3 | 0.0004 | Diamond, 3 Micron | Diamond, 3 Micron |
| Hard Face | 0.2 | 0.4 | 3 | 5 | 0.00027 | Diamond, 6 Micron, 3 Micron | Diamond, 9 Micron, 3 Micron |
| Hard Face | 0.4 | 0.5 | 3 | 4 | 0.0003 | Diamond, 6 Micron | Diamond, 6 Micron |
| Hard Face | 0.45 | 0.8 | 2 | 4 | 0.0002 | Diamond, 6 Micron | Diamond, 6 Micron |

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